DEVELOPMENT AND CONSTRUCTION OF LOW-CRACKING HIGH-PERFORMANCE CONCRETE (LC-HPC) BRIDGE DECKS: CONSTRUCTION METHODS, SPECIFICATIONS, AND RESISTANCE TO CHLORIDE ION PENETRATION

BY

Heather Anne Kirkvold McLeod

Submitted to the graduate degree program in
Civil Engineering and the Graduate Faculty of the
University of Kansas in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy.

____
Chairperson

Committee members ________________________

____

____

____

Date defended: September 1, 2009

The Dissertation Committee for Heather Anne Kirkvold McLeod certifies
that this is the approved version of the following dissertation:

DEVELOPMENT AND CONSTRUCTION OF LOW-CRACKING
HIGH-PERFORMANCE CONCRETE (LC-HPC) BRIDGE DECKS:
CONSTRUCTION METHODS, SPECIFICATIONS, AND RESISTANCE TO
CHLORIDE PENETRATION

____
Chairperson

____

____

____

____

Date approved: ________________

ABSTRACT

The development, construction, and evaluation of Low-Cracking High-Performance Concrete (LC-HPC) bridge decks are described based on laboratory test results and experiences gained through the construction of 14 LC-HPC bridge decks. The study is divided into three parts covering (1) an evaluation of the chloride penetration into concrete using long-term salt-ponding tests, (2) a comprehensive discussion of specifications for LC-HPC construction and standard practices in Kansas, and (3) the description of the construction and the preliminary evaluation of LC-HPC bridge decks in Kansas. This report emphasizes the construction process; a companion report provides a detailed discussion of the influence of material properties on the performance of LC-HPC bridge decks.

The first portion of the study involves evaluating the effect of paste content, curing period, water-cement (*w/c*) ratio, cement type and fineness, mineral admixtures (ground granulated blast furnace slag and silica fume), a shrinkage reducing admixture (SRA), and standard DOT bridge deck mixtures on chloride penetration into solid concrete, tested in accordance with AASHTO T 259. The evaluation includes a total of 33 individual concrete batches and 123 test specimens. The results indicate that for concrete containing only portland cement, reductions in paste content result in increased permeability. A reduced paste content and increased *w/c* ratio result in increased permeability, whereas the presence of mineral admixtures (ground granulated blast furnace slag and silica fume) and longer curing periods result in decreased permeability. Concrete made with medium or coarse ground Type II cement has greater permeability than concrete made with Type I/II cement. It is not clear how the presence of an SRA affects concrete permeability. LC-HPC mixtures have lower permeability than standard DOT mixtures.

The second portion of the study describes the specifications for the LC-HPC and Control bridge decks in Kansas. The focus is on the construction methods, including the evolution of the specifications over time.

The third portion of the study details the development and construction of 14 LC-HPC and 12 conventional Control bridge decks built in Kansas. The design details, construction experiences, and lessons learned from the LC-HPC bridge decks are described in detail, and an overview of the materials is presented; the design and construction data for each Control deck is provided; and initial crack survey results are evaluated for various construction-related parameters. The results indicate that that successful LC-HPC bridge deck construction is repeatable and that clear and consistent communication between the contractor, owner, and testing personnel is vital for successful construction of LC-HPC decks. Preliminary evaluation of cracking indicates that at early ages, LC-HPC decks are performing better than the Control decks, as well as earlier monolithic decks in Kansas.

Keywords: bridge decks, cement fineness, chloride penetration, concrete mix design, concrete pumping, construction methods, cracking, curing, durability, finishing, high-performance concrete, permeability, salt-ponding, shrinkage reducing admixture, slag, silica fume, temperature control

ACKNOWLEDGEMENTS

I want to express my sincere gratitude to my advisors, Professors David Darwin and JoAnn Browning, for their commitment, guidance, support, and advice during my time at the University of Kansas. Gratitude is also expressed to Professors Adolfo Matamoros, Stan Rolfe, and Robert Rowland, for their work as committee members and their guidance during the course of my academic program.

I also want to express gratitude to the Madison and Lila Self Graduate Fellowship at the University of Kansas and to the American Concrete Institute (ACI) for providing professional development opportunities and financial support during my time at the University of Kansas.

I have been honored to work with many colleagues, past and present. I am grateful for the work we have accomplished together and also for your friendship.

Finally, and most importantly, I wish to express my heart-felt thanks to my husband and daughters, David, Jadelin, and Adeline, and to my parents, Darlene and Erwin Kirkvold, for their endless support and encouragement.

H.A.K.M.

TABLE OF CONTENTS

LIST OF TABLES

Table

LIST OF FIGURES

Figure

Chapter 1

INTRODUCTION

1.1 GENERAL

Premature deterioration of concrete bridge decks is a serious problem in the United States that has significant financial and safety consequences. Bridge deck cracking is associated with accelerated corrosion of the reinforcing steel, increased maintenance costs, and shortened service life of the deck. In 2002, almost 30,000 bridge decks in the United States were classified as being in a deficient condition (Walther and Chase 2006), defined according to National Bridge Inspection Standards (NBIS) as “loss of section, deterioration, spalling, or scour have seriously affected primary structural components,” or worse. It is generally recognized that funding levels authorized by Congress have been insufficient to keep pace with the number of NBIS-classified deficient bridges requiring attention (Walther and Chase 2006). The average annual cost of corrosion for bridges in the United States is approximately $8.3 billion (Yunovich et al. 2005), with associated indirect costs due to traffic delays and lost productivity estimated to be ten times the direct costs (Thompson et al. 2005).

Much of these corrosion-related costs can be attributed to corrosion of the reinforcing steel in bridge decks (Virmani and Clemena 1998), which is accelerated by bridge deck cracking and the application of chloride-containing deicing chemicals. It has been estimated that more than 100,000 bridges in the United States have developed early age cracking (Krauss and Rogalla 1996). Researchers and transportation agencies have worked since the early 1960s to solve this problem. Much has been learned about the causes of bridge deck deterioration and cracking, and the strategies required to construct durable structures that are low-cracking, resistant to chloride ingress, and corrosion resistant, with a long service life and reduced life-cycle costs. Yet bridge deck cracking and premature deterioration remain significant problems today.

Materials and structures designed to meet specified performance requirements have been described as being "high performance." The problem of bridge deck deterioration is a perfect application for high performance concrete (HPC). An industry movement toward improving the durability of bridge decks by using HPC has become evident since the 1990s. For many bridge owners, however, implementation of HPC for bridges has not yet achieved the desired results, and in fact, many of the strategies used to achieve "high performance" have been counterproductive. A 2003 Federal Highway Administration (FHWA) nationwide survey of state departments of transportation (DOTs) (Napier and Maruri 2003) indicated that the top three most desired attributes of HPC are (1) crack control, (2) longer service life, and (3) high durability. In stark contrast to these attributes were the results perceived by the DOTs, with the three most desired attributes ranked as the lowest perceived attributes in the survey. At best, a disconnect exists between theory and (perceived) results for HPC.

1.2 FACTORS AFFECTING BRIDGE DECK DURABILITY

Durability can be generally defined as the ability to exist for a long time without significant deterioration (Webster 1984). Deterioration of bridge decks is found in many forms, including cracking, corrosion, scaling, spalling, freeze-thaw damage, abrasion damage, and pop-outs. Methods to prevent some of these types of deterioration are well understood. For example, it is known that air entrainment can prevent scaling, and durable aggregates can help resist abrasion and freeze-thaw damage. Much attention has been focused on the pervasive problem of reinforcing steel corrosion, which causes subsequent cracking and delamination of the concrete and, ultimately, structural failure.

1.2.1 Corrosion in Concrete

Three environmental components must be present for corrosion of steel (containing iron Fe) to occur: oxygen O_2, water H_2O, and the flow of electrons (Jones 1996). The corrosion of reinforcing steel is an electrochemical process that produces hydrated ferric oxide (rust), which requires significantly more volume than the initial materials. The larger volume of the corrosion products causes tensile stresses in the concrete that can eventually lead to concrete cracking and spalling in the area around the reinforcing steel (Mindess et al. 2003). Under normal conditions, reinforcing steel in concrete does not corrode. The alkaline environment of concrete helps to produce a passive oxide film, gamma ferric hydroxide γ-FeOOH, which tightly adheres to the surface of the bar. This passive film protects the steel from infiltration of oxygen and water. The passive film, however, can be destroyed by the presence of chloride ions Cl^-, introduced to the bridge deck by deicing salts such as sodium chloride NaCl and calcium chloride $CaCl_2$. Because the presence of chloride ions destroys the protective passive layer and can also accelerate the rate of corrosion, reinforcing steel is susceptible to corrosion when exposed to chlorides.

Chlorides may be initially present in the concrete materials through the introduction of concrete admixtures, such as $CaCl_2$, contaminated aggregates, or mix water. Deicing salt is the most common vehicle for the introduction of chlorides to the concrete after it has been placed. The transport of chloride ions to the reinforcing steel occurs by one of two critical pathways – through cracks, which provide the fastest and most direct pathway for chlorides to reach the reinforcing steel, and through uncracked concrete. The ingress of the chloride ions through solid concrete can be by a variety of mechanisms, including capillary action and absorption, but the dominant mechanism for uncracked concrete is by diffusion of the ions through the water-filled pore system (Whiting and Mitchell 1992).

1.3 SIGNIFICANCE OF BRIDGE DECK CRACKING

1.3.1 Time to Corrosion Initiation

Though many factors affect the chloride-induced corrosion threshold in bridge decks, a generally accepted value for the chloride concentration in concrete that initiates corrosion of conventional reinforcing steel is approximately 0.6 kg/m^3 (1.0 lb/yd^3). Solid concrete provides substantial protection against diffusion of chlorides. Cracked concrete, however, is another matter. Studies at the University of Kansas have shown that, for cracked concrete, chloride concentrations at the Kansas standard reinforcing steel depth of 76.2 mm (3.0 inches) can reach corrosion threshold levels in as little as nine months and that the majority of bridges decks exceed threshold levels within 24 months (2 years) from the date of construction (Lindquist et al. 2005, 2006). This is in direct contrast with the performance of uncracked concrete where all chloride levels were found to be below corrosion threshold levels for up to 96 months (8 years) and more than 50% of bridge decks could be expected to be below the threshold levels (e.g. not corroding) at up to 254 months (21.2 years). Figures 1.1 and 1.2 (Lindquist et al. 2005, 2006) demonstrate the dramatic difference in chloride concentration levels between cracked and uncracked concrete. The significantly detrimental impact of cracking on the time for corrosion initiation makes it clear that to prevent corrosion damage, attention must first be focused on preventing bridge deck cracking. There is no substitute for uncracked concrete as a protection system. It is not enough to provide (cracked) concrete with low-permeability. Ideally, concrete for bridge decks should be uncracked (primary importance), durable, and effective at resisting chloride ingress (secondary importance).

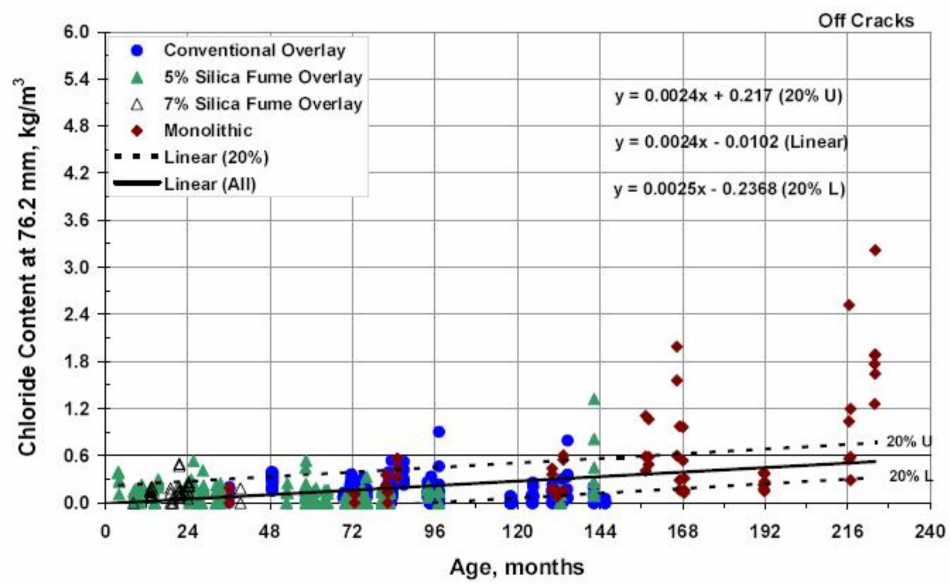


Figure 1.1 Chloride content taken away from cracks interpolated at a depth of 76.2 mm (3.0 in.) versus placement age. Twenty percent upper (20% U) and lower (20% L) bound prediction intervals are included (Lindquist et al. 2005).

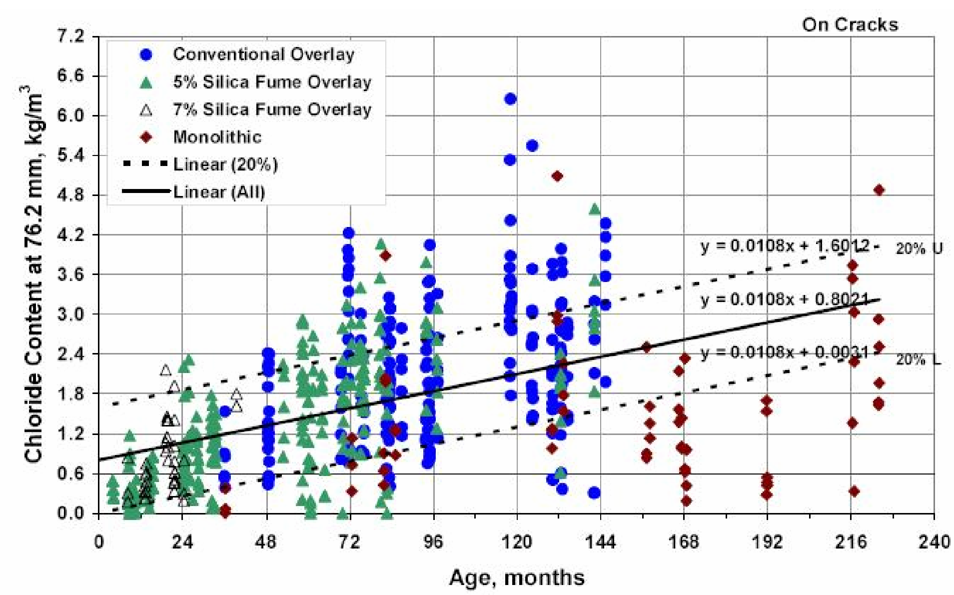


Figure 1.2 Chloride content taken on cracks interpolated at a depth of 76.2 mm (3.0 in.) versus placement age. Twenty percent upper (20% U) and lower (20% L) bound prediction intervals are included (Lindquist et al. 2005).

Corrosion protection systems have been tested and implemented with varying degrees of success. In the United States, epoxy-coated reinforcement (ECR) is the most widely implemented corrosion protection system. The epoxy is meant to act as a physical barrier to the ingress of chlorides and oxygen. A study in Iowa determined that most of the corrosion found on ECR in bridge decks occurred at cracks, and there was no evidence of corrosion of ECR in uncracked locations, even though the chloride concentrations at the bars was higher than threshold limits (Fanous and Wu 2005).

Cracking affects corrosion initiation in bridge decks, even when corrosion protection systems are used, and therefore, is another reason why cracking should be prevented. Besides the work at the University of Kansas, other studies have also indicated that cracking in bridge decks significantly decreases the time to corrosion initiation (Boulfiza et al. 2003, Paulsson-Tralla and Silfwerbrand 2002).

Some studies of corrosion initiation and service life prediction focus only on the diffusion of chlorides through solid concrete to initiate corrosion. Such analyses ignore cracking as the faster transport mechanism. The age at which cracking occurs and the amount and type of cracking will significantly affect the quantity and speed at which chlorides reach the reinforcing steel.

1.3.2 Early Age Cracking

According to bridge deck cracking studies at the University of Kansas, a large percentage of crack density (length of cracks per unit area) is established early in the life of a deck (Lindquist et al. 2005). It was also determined in the Kansas studies that bridge deck cracking increases gradually with time and generally at similar rates for different deck types. The conclusion, therefore, is that to minimize total crack density, it is necessary to limit early age cracking.

1.3.3 Crack Location

The orientation and shape of a crack will significantly affect bridge deck deterioration (Krauss and Rogalla 1996). The exposure that a crack pathway provides for chlorides to reach the reinforcing steel is impacted by the location of the crack with respect to the bar. Bars exposed to a crack that is perpendicular to the bar (and goes down to the level of the bar) will be exposed only at the intersection of the crack and the bar, and possibly, only localized corrosion may occur. Cracks located parallel to and directly over bars expose the entire length of the bars to chlorides, significantly increasing the exposure of the bar, and are likely to result in accelerated corrosion. Unfortunately, much of the cracking on bridge decks corresponds to the second geometric condition, creating a more severe exposure condition. Studies have reported that transverse cracks are the dominant form in bridge decks and that these cracks are generally located directly over the top transverse reinforcing bars (Krauss and Rogalla 1996, Portland Cement Association 1970), creating conditions where corrosion may occur at multiple locations along the bar.

1.4 TYPES AND CAUSES OF CRACKING

Cracking in concrete is, in essence, a simple phenomenon with a complex, interconnected series of causes. Concrete is a brittle material with a maximum tensile strength equal to about one-tenth of its compressive strength for normalweight concrete. Volume changes in concrete occur over time due to drying shrinkage and temperature differentials. Unrestrained concrete can undergo large volume changes without causing tensile stresses that result in cracking. When restraint (internal or external) is introduced, however, concrete can develop stresses that exceed its tensile capacity, which will result in cracking. For a given loading condition, cracking can be mitigated by improving the material's capacity to relieve the tensile stresses (increased creep), by limiting the volume change, or by limiting the restraint.

Cracking in concrete bridge decks can generally be classified by the causes of the cracking. The observed physical characteristics and orientation of the cracks can also be helpful in determining the cause of the cracking.

1.4.1 Plastic Shrinkage Cracking

Plastic shrinkage cracking occurs at the surface of exposed plastic concrete when the evaporation rate exceeds the rate at which concrete bleed water reaches the surface of the concrete. Tensile stresses are created in the capillary pores as the concrete surface dries. Because the concrete is still plastic, it has no capacity to resist these stresses, and the concrete cracks. Weather and construction conditions, such as high air and concrete temperatures, high wind speeds, and low relative humidity, increase the evaporation rate and cause exposed plastic concrete to be susceptible to plastic shrinkage cracking. The nomograph shown in Fig. 1.3 relates air temperature, relative humidity, concrete temperature, and wind speed to the rate of drying and is used to estimate the evaporation rate at the surface of plastic concrete. If weather and material conditions are measured accurately and frequently, this nomograph can help to give general guidance in the field as to when conditions are ripe for plastic shrinkage cracking. It is generally accepted that the probability of plastic shrinkage cracking is reduced when the evaporation rate is below 1 $kg/m^2/hr$ (0.2 $lb/ft^2/hr$). Concrete material properties, however, affect the bleed rate and, thus, affect the susceptibility of concrete to plastic shrinkage cracking. The presence of mineral admixtures and entrained air decrease the bleeding rate of concrete, as do decreased water-cementitious material (*w/cm*) ratio, increased fineness of the cement, and an increased hydration rate. The use of water reducers for the purpose of reducing water content of a mixture will also reduce the bleeding capacity of the concrete.

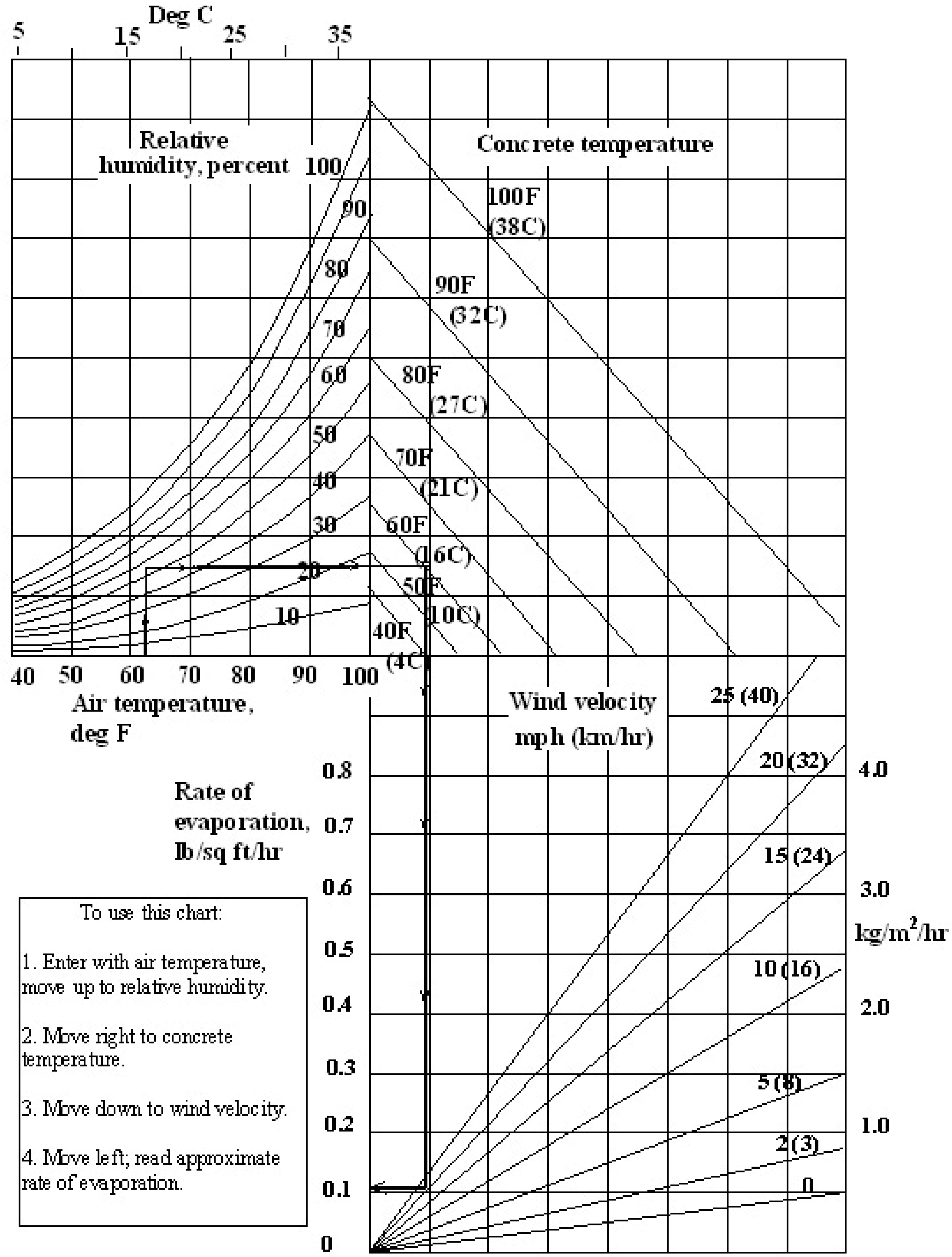


Figure 1.3 The evaporation rate nomograph (ACI 308-92 1997).

The solutions to the problem of plastic shrinkage cracking are well understood, although the remedies can be difficult to successfully implement. Either the evaporation rate must be reduced, or the bleed rate of the concrete must be increased or both. The evaporation rate can be reduced by covering plastic concrete with polyethylene sheeting, not placing concrete at elevated air temperatures, controlling the concrete temperature, maintaining an area of high relative humidity just above the entire surface of exposed plastic concrete by using effective fogging equipment, and by constructing wind breaks. The most effective remedy to plastic shrinkage cracking for finished concrete is the immediate placement of a wet curing material, such as burlap, maintained in the wet condition.

1.4.2 Settlement Cracking

Settlement cracking refers to cracks that form in plastic concrete directly above and parallel to reinforcing bars caused by local tensile stresses influenced by the presence of reinforcing steel. After placement and consolidation, but while the concrete is still plastic, local planes of weakness can form above the bar due to continuing subsidence of the concrete around a fixed reinforcing bar. A small amount of bleed water may also be trapped under the bar, adding another point of weakness. These vertical planes of weakness serve as crack initiation sites in the plastic concrete and also in the hardened concrete once tensile stresses begin to develop (Babaei and Purvis 1995b). Inadequate consolidation during bridge deck construction will increase the amount of settlement and settlement cracking. The amount of settlement cracking can be reduced with reduced concrete slump, increased cover, and reduced reinforcing bar size (Dakhil et al. 1975).

1.4.3 Thermal Cracking

Thermal cracking in bridge decks is caused by concrete expansion and shrinkage due to thermal loading, restrained by the reinforcing steel, girders and bridge end conditions. Thermal loading occurs from the heat of hydration, diurnal or seasonal weather, or high initial concrete temperature followed by subsequent cooling. Heat generated by the hydration reactions causes temperature increases in the concrete, and the concrete expands. After peak hydration temperatures are reached and the concrete has hardened, the concrete cools and contracts. The girders and reinforcing steel restrain the contracting concrete, inducing tensile stress within the concrete deck and causing cracking if the stress reaches the concrete tensile capacity.

1.4.4 Drying Shrinkage Cracking

Drying shrinkage cracking occurs in hardened concrete due to the loss of water (drying) from the concrete resulting in volumetric shrinkage. Water loss occurs from the capillary pores in the cement paste, primarily from the C-S-H gel, and to a lesser extent from the solid surfaces. Bridge decks are restrained from shrinkage primarily by the reinforcing steel and the girders. Drying gradients throughout deck cross-sections also promote increased tensile stresses at the drying surface due to restraint from higher moisture-content concrete in the midsection of the member. Because of the long-term nature of concrete drying (up to one year), some of the tensile stress is offset by concrete creep. Therefore, the rate of drying shrinkage can be an important factor as it relates to cracking. Reducing the rate of drying will enhance the effect of creep to mitigate drying shrinkage.

Drying shrinkage is affected by the material properties of the concrete. Because cement paste (water and cement) is the portion of the concrete that shrinks, an increase in paste content leads to more drying shrinkage. Aggregate provides restraint and does not shrink. Therefore, maximizing the aggregate content reduces the amount of drying shrinkage. Cement fineness, the presence of mineral admixtures, and the air content of concrete all affect the amount and rate of drying shrinkage. Cement that is ground finely decreases the diameter of the capillary pores, creating greater internal pore-pressure and increased shrinkage. Some mineral admixtures, such as ground granulated blast furnace slag (GGBFS) and silica fume have been shown to reduce drying shrinkage in concrete, whereas fly ash has been shown to increase shrinkage. Entrained air in the concrete may reduce the volume of paste required to achieve a given workability and can, therefore, reduce drying shrinkage.

The rate of drying shrinkage and the stress gradients that result from drying shrinkage are influenced by design and construction practices. The thickness of a bridge deck influences the surface area-to-volume ratio and, therefore, the rate of drying of the bridge deck. Stay-in-place (SIP) forms prevent the deck's bottom surface from drying and induce drying shrinkage gradients throughout the deck cross section. The degree of hydration affects drying shrinkage. Longer curing and increased age of concrete prior to first drying will decrease drying shrinkage. If cement paste is dried slowly, at progressively lower relative humidities, the total shrinkage is less than if dried directly at the lowest relative humidity (Mindess et al. 2003).

For bridge decks, the primary factors that affect shrinkage are the concrete materials, construction techniques, bridge geometry, and environmental conditions (Krauss and Rogalla 1996).

1.4.5 Orientation of Cracks

The orientation of cracks and when they occur in the life of bridge decks can help to identify causes of cracking and, therefore, methods of prevention. The forms of bridge deck cracking that significantly affect bridge deck durability are reviewed.

<u>Transverse Cracking</u>

Transverse cracking has been found to be the predominant and most detrimental type observed on bridge decks (Babaei and Purvis 1995b, Eppers et al. 1998, Krauss and Rogalla 1996, Le et al. 1998, Lindquist et al. 2005, Portland Cement Association 1970). Transverse cracks are perpendicular to the bridge deck centerline, typically straight, and extend a significant portion of the distance across the bridge deck in both positive and negative moment regions (Babaei and Purvis 1995b, Krauss and Rogalla 1996, Lindquist et al. 2005). They are frequently full-depth cracks and, in most cases, occur directly over transverse reinforcing bars

(Babaei and Purvis 1995b, Krauss and Rogalla 1996). Reinforcing steel is exposed along the entire length of the crack and is, thus, subject to direct chloride ingress and moisture, resulting in the most severe exposure condition possible for reinforcing steel in a bridge deck. Transverse cracking may occur and become visible before the bridge deck is open to traffic or at some later date (Portland Cement Association 1970).

Transverse cracking can be caused by inadequate cover, inadequate consolidation, settlement cracking, or drying shrinkage cracking and may be enhanced by plastic shrinkage. The presence of a reinforcing bar delineates a plane of weakness as discussed previously in the settlement cracking section.

Longitudinal Cracking

Longitudinal cracks are parallel to the bridge deck centerline, typically straight and vary in length. Longitudinal cracking may be full-depth and can be observed before the deck is open to traffic or at some later date (Portland Cement Association 1970). Longitudinal cracking may occur at a fixed abutment (Lindquist et al. 2005).

Diagonal Cracking

Diagonal cracks form an angle other than 90 degrees with the centerline of the bridge deck. They are typically shallow in depth (Portland Cement Association 1970) and usually occur near the ends of skewed bridges and over single-column piers (Lindquist et al. 2005). They may be found immediately after construction or after the bridge is open to traffic. The causes of diagonal cracking are believed to be flexural restraint and differential drying shrinkage in the decks near the abutments in skewed bridges (Portland Cement Association 1970).

Map Cracking ("Crazing")

Map cracking is an interconnected system of cracks of any size (Portland Cement Association 1970). Cracks are generally shallow and are usually not associated with reinforcing steel (Portland Cement Association 1970) and therefore, are considered to have minimal effect on bridge deck durability. Map cracking is thought to be primarily caused by plastic shrinkage cracking or drying shrinkage cracking (Portland Cement Association 1970).

1.5 FACTORS AFFECTING CRACKING

The dominant factors affecting bridge deck cracking are the degree of restraint within the deck, the concrete material's effective modulus (including creep effects), and concrete volume change due to thermal and shrinkage effects (Krauss and Rogalla 1996). These factors are controlled by the design, by the concrete material used in the bridge deck, and by the construction practices.

1.5.1 Design

The primary design factors that influence bridge deck cracking include the girder support condition (fixed or pinned), girder type, and deck reinforcing bar size (French et al. 1999b, Krauss and Rogalla 1996, Lindquist et al. 2005, Miller and Darwin 2000, Schmitt and Darwin 1995). Bridges with fixed girders exhibit more cracking than bridges with pinned supports. It is generally accepted that steel girder bridges exhibit more cracking than concrete girder bridges (Cheng and Johnston 1985, Krauss and Rogalla 1996, Perfetti and Johnston 1985, Portland Cement Association 1970). Larger reinforcing bar size increases the cracking tendency for a deck.

The design controls the amount of restraint in the system. Increased restraint resists shrinkage strain in the deck, increasing tensile stresses and the likelihood for cracking to occur. Minimizing restraint in bridge deck systems helps to minimize cracking. Restraint can be reduced by using pinned end instead of fixed end supports, concrete girders instead of steel girders, and systems with smaller sized girders and thicker decks (Krauss and Rogalla 1996). A restraint coefficient, proposed by Ducret et al. (1997), relates girder cross sectional area with deck cross sectional area, as described in Section 1.7.2. Deck thickness and girder design can, therefore, influence deck cracking.

The deck thickness influences drying shrinkage (Section 1.4.4) and thermal effects (Sections 1.4.3 and 1.7), and, therefore, affects cracking.

Prestressed concrete girder bridges are typically designed to have camber that increases early in the life of the bridge. This increasing camber induces tensile stresses in the top of the deck and may increase cracking.

1.5.2 Concrete Material Properties

Concrete that is designed to have low-shrinkage and low-cracking characteristics plays an important role in the construction of bridge decks with minimal cracking. Concrete material properties as they affect plastic shrinkage cracking, settlement cracking, thermal cracking and drying shrinkage cracking are discussed in Section 1.4. The primary material properties that influence bridge deck cracking can be summarized as the paste content (volume), air content, compressive strength, and the cementitious materials, including mineral admixtures (Babaei and Purvis 1996, Cheng and Johnston 1985, Eppers et al. 1998, Krauss and Rogalla 1996, Lindquist et al. 2005, Schmitt and Darwin 1999, Whiting and Detwiler 1998). Cracking tendency increases with increases in paste (water and cement) content, compressive strength, and decreasing air contents below 6%. The increase in cracking related to increased compressive strength also correlates with decreased *w/cm* ratio, increased modulus of elasticity, and reduced tensile creep. The effect of mineral admixtures on cracking is unclear.

1.5.3 Construction Practices

It is generally recognized that construction practices affect the cracking tendency of concrete bridge decks. Weather on the date of casting and curing practices significantly influence the cracking tendency of bridge decks (Cheng and Johnston 1985, Eppers et al. 1998, Krauss and Rogalla 1996, Lindquist et al. 2005, Poppe 1981). Ensuring adequate consolidation and controlling concrete temperature are also important in controlling cracking. Construction practices, as they affect plastic shrinkage cracking, settlement cracking, thermal cracking, and drying shrinkage cracking, are discussed in Section 1.4 Curing practices and weather-related practices must protect the concrete from evaporation during casting and for the entire curing period. Extremes in air temperature, either hot or cold, high wind and high concrete temperature can produce conditions of high evaporation for exposed concrete. When warm concrete is cast in cool weather, there is risk for high evaporation conditions because the concrete heats the air directly above the concrete surface, lowering the humidity, increasing evaporation from the concrete surface. The heated air absorbs moisture and is then replaced by more cold dry air (Krauss and Rogalla 1996). Limiting and protecting against these types of severe exposure is necessary to prevent cracking in bridge decks. Effective fogging and immediate placement of pre-wet curing materials can help to prevent cracking. Controlling concrete temperatures prevents excessive evaporation rates and can prevent cracking due to thermal stresses. Ensuring adequate consolidation is necessary to limit the potential for settlement cracking.

1.6 PERMEABILITY

Limiting cracks is of primary importance in protecting bridge deck reinforcing steel from corrosion, because cracks provide a direct pathway for chlorides to reach the reinforcing steel and initiate corrosion (Boulfiza et al. 2003, Lindquist et al. 2005, Paulsson-Tralla and Silfwerbrand 2002). Of secondary consideration, however, is the prevention of chloride ingress through solid concrete – a matter also worthy of attention. Once the construction of solid, uncracked concrete bridge decks is ensured, the next consideration of importance for the prevention of corrosion is to provide concrete that prevents the ingress of chlorides.

For uncracked concrete in bridge decks, the diffusion of chloride ions through the capillary pores is recognized as the dominant mechanism for chlorides to reach the reinforcing steel and initiate corrosion. The driving force for diffusion is the difference in chloride ion concentration present at different locations within the concrete. Ions generally move from areas of high ion concentration areas to areas of low concentration. Due to the wetting and drying cycles experienced by bridge decks, some transport of chlorides also occurs by the mechanism of capillary absorption, the absorption of water and chlorides due to capillary suction forces. These forces are inversely proportional to the diameter of the capillary pore system.

Many concrete material parameters affect the rate of chloride ingress through uncracked concrete. Chloride diffusion is generally reduced as the *w/cm* ratio decreases and as the length of curing increases. It is generally recognized that the presence of mineral admixtures, such as silica fume (SF), ground granulated blast furnace slag (GGBFS) and fly ash (FA) can significantly reduce the penetrability of uncracked concrete. It is unclear, however, how some chemical admixtures, such as shrinkage reducing admixtures, affect permeability. Others, such as organic corrosion inhibitors, may reduce pore size or total porosity.

Construction considerations, such as the degree of consolidation, plastic concrete temperature, and curing methods, can also affect concrete penetrability. Incomplete consolidation may result in concrete with entrapped air and high porosity and, thus, lead to increased permeability. The pore structure of the cement paste is of little consequence in terms of durability if the concrete contains many entrapped air voids and bleed-water channels (Detwiler et al. 1991). On the other hand, extreme overconsolidation may lead to segregation and increased paste contents near the surface (Neville 1997), allowing greater chloride penetration. Concrete temperature during casting and curing also affects the penetrability of the concrete. Detwiler et al. (1991) reported that portland cement concrete cast and cured at reasonably elevated temperatures, results in a coarser pore structure and corresponds with a decrease in resistance to chloride diffusion. This was concluded based on specimens cast at 35ºC (95ºF) and cured at 50ºC (122ºF), as compared to specimens cast and cured at 20ºC (68ºF). Concrete cast at elevated temperatures can also cause construction complications, such as reduced workability, short time-of-set, poor consolidation, and plastic shrinkage cracking due to high evaporation rates. Curing methods, such as wet curing or using curing compound, and the length of curing will also affect the chloride penetrability (Hooton et al. 2002). Ideally, continuous wet curing for as long as possible will achieve maximum impenetrability for a given concrete mixture. Premature drying of concrete will result in higher porosity and compromise the ability of the concrete to resist chloride ingress.

The exposure conditions, once the bridge deck is in service, also significantly affect diffusion rates (Suryavanshi et al. 2002). Exposure of hardened cement pastes, after wet curing for 28 days, to elevated temperatures up to 60ºC (140ºF) can irreversibly change the pore structure of the concrete and increase permeability (Atkinson and Nickerson 1984). Cyclic wetting and drying conditions will increase the diffusion of chlorides into concrete, compared to constant ponding conditions.

1.6.1 Test methods

A variety of laboratory test methods are available to evaluate chloride ingress or the potential for chloride ingress into concrete. Testing can generally be split into two categories, those that directly measure chloride ingress into concrete and those that produce indirect measures of penetrability, usually used when a shorter testing period is desired.

Direct Chloride Testing

Direct testing of chloride ingress typically includes some form of specimen exposure to a chloride solution. After a period of time, samples are taken from the concrete to determine the chloride content. The methods of exposure and sampling vary. Direct testing methods are typically considered to be long-term tests taking more than 30 days.

The AASHTO T 259 (2002) and the ASTM C1543 (2002) are ponding test methods that provide a direct measure of chloride ingress into non-saturated concrete. Small slab specimens are exposed to an aqueous chloride ion solution of known concentration by ponding for 3 months or more. After the exposure period, samples are taken from the specimens at various depths and tested for chloride ion concentration. A profile of chloride concentration levels throughout the depth of the concrete is established. Concrete properties, such as the effective diffusion coefficient and the apparent surface concentration, can be mathematically estimated using Fick's Second Law. The chloride profile and the effective diffusion coefficient serve as a measure of the material's ability to resist ingress of chloride ions in the uncracked condition. Chloride concentration levels of samples from these tests are determined using methods such as ASTM C1152/C 1152M (2004) or AASHTO T 260 (2001).

ASTM C1556 (2004) and NordTest NT Build 443 (1995) are two other test methods that provide direct testing of the chloride ingress into concrete in the saturated condition. Core specimens, either drilled or cast, are immersed in sodium chloride solution for an exposure period, usually a minimum of 35 days, then a profile of chloride concentration levels is determined and the effective (apparent) diffusion coefficient is calculated according to Fick's Second Law. It should be noted that ASTM C1556 does not account for chloride binding effects because the total chloride content (acid-soluble) is measured (Nokken et al. 2006). Any chloride ion analysis preformed for total chloride content (acid-soluble) will neglect the effects of chloride binding, whereas water-soluble chloride content testing will better account for the effects of binding.

Indirect Testing

Because of the long-term nature of direct testing, faster testing methods are often desired. Indirect testing methods can be used based on the assumption that the indirect measures correlate with a concrete's ability to resist chloride ion penetration.

The water absorption method, ASTM C1585 (2004) determines the rate of absorption (sorptivity) of water by measuring the increase in mass with time of an unsaturated specimen exposed to water. The mechanism for the ingress of water in this test is dominated by capillary suction, and is meant to determine the susceptibility of unsaturated concrete to the penetration of water alone. It does not measure chloride ingress. Other methods have been developed to measure the volume or weight of water absorbed by a concrete specimen in a short period of time (less than one day) (Durham et al. 2005).

Measurement of the electrical conductivity of concrete is a popular method for evaluating potential chloride ingress. ASTM C1202/AASHTO T 277, Test Method of Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration (2007) is the most commonly used electrical conductivity testing method, particularly in the United States. First developed as an in-situ field test, the method is based on the ability of a specimen to conduct electrical current. The test consists of measuring the amount of electrical charge (in Coulombs) passed through a vacuum-saturated concrete core over a 6-hour period. The specimen is sandwiched between two solutions, sodium chloride and sodium hydroxide, and a constant potential difference is maintained across the specimen. The total charge passed through the specimen is recorded and considered to be an indication of the concrete's permeability or resistance to chloride ion penetration.

Though widely used for acceptance testing and quality control, this test method itself includes multiple caution statements regarding the use of the results to evaluate the permeability of field concrete for acceptance purposes. The test method must be used with caution, especially for acceptance testing and quality control applications (AASHTO T 277–07 2007). Test results are a function of the electrical resistance of the specimen itself, as affected by *w/cm* ratio, curing time, curing procedures (Whiting and Mitchell 1992), material content, mineral admixtures, chemical admixtures, curing, surface applications and treatment, presence of reinforcing steel, sample age, maximum aggregate size, specimen diameter and moisture content. Any material used as a constituent of concrete that causes the concrete to be more or less conductive will increase or decrease the measured charge passed through the specimen, irrespective of whether such materials actually affect permeability, diffusion, or other ion transport mechanisms.

Combination Testing

The NordTest NT Build 492 (1999) and the Rapid Migration Test (Luping and Nilsson 1992) are testing methods that use electrical potential to force chloride migration into a specimen, then directly measure chloride ingress into the specimen. To measure the depth of chloride ingress, the specimens are split axially and a silver nitrate solution is applied to the surface and the chloride penetration depth is measured from the visible, white silver chloride precipitate. These test methods are meant to be improvements upon the RCPT method, maintaining reasonable testing temperatures and measuring the actual depth of chloride penetration, not just the total ionic movement.

1.6.2 Modeling Chloride Diffusion

The ingress of chloride ions into solid concrete is a complicated chemical and physical process, dependant on multiple transport mechanisms and chemical interactions. It is generally accepted that diffusion is the dominant mechanism by which chlorides migrate through concrete. Ions generally move from areas of high ion concentration toward areas of low ion concentration.

Diffusion of chlorides into solid concrete is commonly modeled using Fick's second law, as shown in Eq. (1.1).

$$\frac{\partial C(x,t)}{\partial t} = D\left(\frac{\partial^2 C(x,t)}{\partial x^2}\right) \tag{1.1}$$

where:

$C(x,t)$ = chloride concentration at depth x and time t, kg/m^3 (lb/yd^3)

D = diffusion coefficient, mm^2/day (in.^{2}/day)

x = depth, mm (in.)

t = time, day

Fick's equation generally models chloride migration through concrete based on several assumptions. The material is assumed to be permeable and homogeneous. The diffusion properties of the material are assumed to be constant with time, regardless of the concentration of the diffusant. Diffusion is assumed to occur one dimensionally, perpendicular to the surface of the slab. It is also assumed that no chemical binding occurs between the cement matrix and the chlorides during hydration or diffusion. In reality, chloride diffusion through concrete violates many of these assumptions. Concrete is a non-homogeneous material whose properties, including diffusivity, change with time and with the advancement of the hydration process. The diffusion of chloride into concrete generally decreases with time due to many factors, such as continued hydration, reduction in the connectivity of the capillary pore system, and the deposition of ions in the pores restricting ("clogging") the flow through the concrete, particularly in areas near the surface where deicing chemicals are applied. Aluminates in young concrete can also chemically bond with chloride ions, preventing further diffusion (Whiting and Detwiler 1998). Although chloride diffusion through concrete is a time-dependent process controlled by numerous parameters, the estimation of diffusion coefficients is still considered a useful tool for comparing concretes ability to resist chloride ion penetration.

The most common method of solving Eq. (1.1) assumes that the diffusion coefficient of the concrete is constant over time, hence calling it an effective diffusion coefficient D_{eff}. A boundary condition and initial condition for the differential equation are also assumed. The initial chloride content in the concrete prior to testing is assumed to be zero (initial condition is $C(x,t) = 0$ at $x > 0$ and $t = 0$), and the surface chloride concentration at the ponded surface of the specimen is assumed to be constant over time (boundary condition is $C(x,t) = C_o$ at $x = 0$ and $t > 0$). Using these assumptions and Crank's solution to Eq. (1.1) (Lindquist et al. 2006), the chloride concentration as a function of depth and time is

$$C(x,t) = C_o\left[1 - erf\left(\frac{x}{2\sqrt{D_{eff} \times t}}\right)\right] \tag{1.2}$$

where:

C_o = apparent chloride concentration at the surface (at depth $x = 0$ for all times t), kg/m^3 (lb/yd^3)

D_{eff} = effective diffusion coefficient, mm^2/day (in.^{2}/day)

erf = the error function

The initial chloride concentration in the concrete can be measured or assumed. If the initial background chloride concentration is measured or assumed to be anything other than zero, then the solution is

$$C(x,t) = C_i + (C_o - C_i)\left[1 - erf\left(\frac{x}{2\sqrt{D_{eff} \times t}}\right)\right] \tag{1.3}$$

where:

C_i = initial "background" chloride concentration in concrete (at time $t = 0$ and all depths x)

The apparent surface chloride concentration C_o and the effective diffusion coefficient D_{eff} are determined by fitting Eq. (1.2) to measured chloride profiles in concrete exposed to chlorides using the nonlinear regression analysis least squares fit method. The effective diffusion coefficient and the (constant) apparent chloride concentration are parameters by which concrete materials may be compared for their resistance to chloride ion penetration.

1.7 THERMAL STRESSES AND TEMPERATURE CONTROL OF CONCRETE

Bridges are subject to continuously changing temperatures and temperature gradients from the initiation of construction. Although temperature changes as it relates to cracking are not often considered during the design of bridge decks, thermal loading significantly impacts the behavior of bridges, and tensile stresses from thermal effects are inevitable in bridge decks. Research has shown that thermal loading is a primary factor that influences cracking in bridge decks (Babaei and Purvis 1996, Cheng and Johnston 1985, French et al. 1999b, Krauss and Rogalla 1996, Lindquist et al. 2005). Some researchers believe that early cracking in bridge decks is principally due to the effects of thermal stresses from hydration of the concrete as it relates to the bridge restraint conditions (Ducret et al. 1997).

Researchers have considered the effects of thermal stress on bridge deck cracking. Stress can be induced in the bridge deck due to both the expansion of the concrete during the hydration process and the contraction of the concrete after the concrete has set and the peak hydration temperatures have been reached. As the concrete cools and contracts, the bridge girders provide restraint and tensile stresses are induced in the deck. These tensile stresses can cause cracking in young concrete or increase the probability of cracking under subsequent loading. Material properties, construction methods and techniques, and design factors influence this thermally induced stress. Critical factors that influence thermal stress include the initial temperature of the plastic concrete, peak hydration temperature, temperature rise in the concrete during hydration, the rate of cooling of the concrete after peak temperatures are reached, curing methods and time, solar radiation and weather conditions. The type of cement, weather, and initial temperature of the plastic concrete affect the peak concrete temperature during curing. Concrete materials and construction practices strongly influence the thermal characteristics of the system.

Retarders, mineral admixtures, and aggregate type affect the modulus of elasticity of the concrete, which changes with time.

1.7.1 Thermal Loading

Hydration

The first thermal loading occurs in concrete bridge decks due to hydration effects during the first days after the deck is cast. The cementitious material hydrates and generates significant heat during the first one to two days after deck placement. Peak temperatures are often reached within 12 to 24 hours after placement (Ducret et al. 1997, Transportation Research Board 2006). The increase of temperature is generally in the range of 15–30ºC (59–86ºF), or approximately 25ºC (77ºF) above the external ambient temperature, and varies depending on the concrete material, deck geometry, initial temperature of the concrete, curing, and weather conditions. Concrete expands as it heats up. While in the plastic state or at very low strengths, this expansion does not induce significant stresses in the concrete. As the concrete hardens and begins to gain strength, stresses due to temperature changes begin to accumulate in the deck. Expansion in concrete that has begun to gain strength will induce compressive stresses in the deck. Concrete set usually occurs before the time that peak temperatures are reached. After peak hydration temperatures are reached, the concrete begins to gradually cool to match the ambient temperature conditions of the air and girders. The cooling period generally lasts between 150 and 180 hours (Ducret et al. 1997). This cooling results in thermal shrinkage of the deck, with the girders providing restraint to this volume change, inducing tensile stresses in the deck. Girder temperature is often assumed to be uniformly equivalent to the ambient air temperature. Field measurements have shown this may be approximately true for the bottom flange, but it is not the case for the top flange (Ducret and Lebet 1997, Wojcik et al. 2003). The temperature of the top flange is approximately the same temperature as the concrete deck. Research indicates that this early age thermal loading has a greater impact on the cracking of bridge decks than does later thermal loading due to weather induced temperature gradients (Ducret and Lebet 1997, Krauss and Rogalla 1996). Research also indicates that early age thermal loading (due to heat of hydration) can induce early-age cracking in decks (Ducret and Lebet 1997).

The magnitude of the temperature increase during hydration is dependant on the plastic concrete temperature, the type, amount and fineness of the cement, the paste content, weather (including solar radiation) during placement and until the cooling process is completed, curing procedures, the deck thickness, the use of retarders, and the use of mineral admixtures. A general rule of thumb is that concrete temperature will rise approximately 7–8 ºC (13–15º F) for every 60 kg/m^3 (100 lb/yd^3) of cement in concrete. Historically, cements manufactured today are ground more finely than cements produced in the past (Portland Cement Association 1996). Therefore, modern cements exhibit higher early strength gains (higher early modulus of elasticity), and result in a higher heat of hydration (peak temperatures) than cements of the past. These characteristics all increase thermal stresses and aggravate cracking.

Temperature gradients in the slab and the girders exist during early-ages due to heat in the deck from hydration (Ducret and Lebet 1997, Wojcik et al. 2003) where the top flange of the girder may be approximately the same temperature as the hydrating deck, but the bottom flange of the girder can be the same as the ambient air temperature. The temperature difference between the peak deck temperature during hydration and the ambient air temperature (and the bottom flange of the girders) can be assumed to be on the order of 25ºC (77ºF) (Ducret and Lebet 1997).

Though many state DOTs specify a maximum plastic concrete temperature of 32ºC (90ºF) (Russell 2004), concrete temperatures above 27ºC (80ºF) can contribute to cracking on bridge decks (Krauss and Rogalla 1996, Portland Cement Association 1970). Minimizing the concrete temperature at placement and the peak concrete temperature during hydration will help to prevent excessive thermal gradients.

Seasonal

Uniform, full-depth thermal stresses induced in bridge decks by seasonal weather changes are considered to have minimal effect on cracking in bridge decks (Krauss and Rogalla 1996). These stresses are caused by the differences in the coefficient of thermal expansion of the concrete and the other materials, such as the reinforcing steel or steel girders. Because the coefficient of thermal expansion for steel ($11–12\times10^{-6}$/ºC)($6.1–6.7\times10^{-6}$/ºF) is typically higher than concrete ($7.4–13\times10^{-6}$/ºC)($4.1–7.3\times10^{-6}$/ºF) (Mindess et al. 2003), a uniform, full-depth temperature increase will cause steel girders to expand more than the concrete deck. Tensile stresses on the order of 2.0 MPa (290 psi) may be induced in the deck over interior supports of a continuous bridge (Krauss and Rogalla 1996).

Diurnal

Some researchers believe that diurnal temperature changes cause the largest thermal stresses in bridge decks (Krauss and Rogalla 1996). Solar radiation can exaggerate the temperature cycles in concrete bridge decks and cause temperature differentials to be larger than the ambient air temperature cycles. The diurnal temperature cycle for bridge decks in moderate to extreme climates can easily exceed 28º C (50º F) (Krauss and Rogalla 1996). Because the bottom side of the deck is not exposed to the solar radiation, the temperature in a bridge deck is rarely uniform and temperature gradients usually exist. A parametric study by Krauss and Rogalla (1996) showed that linear temperature gradients cause greater stresses in the deck than uniform temperature changes and, thus, produce a greater risk of transverse cracking. They reported, for example, that diurnal thermal tensile stresses may exceed 9.6 MPa (1400 psi) for continuous-span steel girder bridges at interior supports, far exceeding the tensile capacity of the concrete and, thus, may cause cracking.

1.7.2 Thermal Stresses

Thermal stresses are induced in a bridge deck due to thermal loading, as described in Section 1.7.1. The primary factors affecting temperatures and thermal stresses in bridge decks are the concrete material properties, bridge design, construction techniques, and the weather conditions. Bridge design conditions affect the amount of restraint provided by the system, thus affecting the magnitude of the residual stresses in the deck due to thermal effects.

Concrete Material Properties

The concrete material properties have a significant effect on the thermal stresses in a bridge deck. Generally, thermal stresses are proportional to the concrete modulus of elasticity, increasing with increasing modulus. The modulus of elasticity of the concrete and the associated creep at a given age are important factors in bridge deck cracking because they determine the tensile stress in the concrete for a given shrinkage strain. These material properties (modulus and creep) affect thermal and shrinkage stresses more than any other property (Krauss and Rogalla 1996). Reducing the concrete modulus of elasticity and increasing creep will reduce thermal and shrinkage stresses and helps to prevent cracking. Using low-modulus aggregates, decreasing the paste content and using lower-strength pastes will reduce the modulus of elasticity of the concrete, although high-modulus aggregates tend to reduce shrinkage strain.

The thermal properties of the concrete affect the thermal stresses in a bridge deck. Thermal stresses due to full-depth temperature changes are linearly proportional to the concrete coefficient of thermal expansion. Thermal stresses and transverse cracking can be reduced by using concrete with a lower coefficient of thermal expansion. Aggregate tends to have a lower coefficient of thermal expansion (6–13×10^{-6}/ºC)(3.3–7.2×10^{-6}/ºF) than cement paste (18–20×10^{-6}/ºC)(10–11×10^{-6}/ºF) (Mindess et al. 2003), thus, increasing the aggregate content in a concrete mix will reduce the coefficient of thermal expansion for the concrete. The type of aggregate used will also have an impact on the thermal properties of the concrete. For example, for a constant aggregate content, concrete made with limestone will be less expansive than those made with granite, which in turn will be less expansive than those made with quartzite. Table 1.1 provides typical values for coefficients of thermal expansion of different concrete materials.

Table 1.1 Coefficient of thermal expansion for materials used in concrete (Mindess et al. 2003)

Material	Coefficient of Thermal Expansion (10^{-6}/ºC)	(10^{-6}/ºF)
Limestone	6	3.3
Granite	7–9	4–5
Quartzite	11–13	6.1–7.2
Cement Paste	18–20	10–11
Concrete	7.4–13	4.1–7.3
Steel	12–12	6.1–6.7

Construction Techniques

Construction techniques significantly impact concrete temperatures (Krauss and Rogalla 1996, Wojcik et al. 2003) and, therefore, can impact the thermal stresses in the concrete. The two construction-related considerations that provide an immediate effect on the thermal stresses in the concrete deck are concrete temperature during placement and curing practices. The temperature of the concrete, as it is placed, dramatically affects the hydration reaction and peak thermal stresses and time to peak temperature. Cooler concrete reacts more slowly, has less tendency toward plastic shrinkage cracking, has lower peak hydration temperatures, and sets more slowly, thus allowing for more dissipation of heat before the concrete sets and begins to accumulate strain due to temperature change. The net temperature change producing strain (after set) is reduced and, thus, thermal stresses are minimized. Early-age curing practices also greatly impact the thermal stresses. Immediate application of wet curing after strikeoff will not only avoid plastic shrinkage cracking, but will also help to minimize concrete temperatures during the initial hydration period. Application of curing material, such as wet burlap, also minimizes the exposure to direct sunlight if placement occurs during daylight hours.

Weather Conditions

Midday peak air temperatures and solar radiation acting on the concrete at the time of set and during the initial period of temperature rise (due to hydration) increases the concrete temperature and speeds up hydration. Faster temperature rises and larger overall temperature rises in the deck are the result. Placement time should be chosen so as to avoid the peak hydration temperature occurring at the same time as the peak air temperature and solar radiation. Set time for the concrete, concrete temperature during placement, and the use of retarders must be taken into account when determining the optimum placement time to reduce peak hydration temperatures, thermal stresses, and cracking.

For steel girder bridges, placing concrete during warm weather is the most advantageous, but only if the concrete temperature is controlled. If concrete is placed when the girders are warm and are the longest (late afternoon to early evening during the summer is the optimum), then when the ambient air temperature decreases, due to diurnal or seasonal effects, girder shortening will act as a countermeasure to the thermal and shrinkage tensile stresses in the concrete deck. Concrete typically has a lower coefficient of thermal expansion than steel. Therefore, a uniform temperature decrease (such as due to seasonal temperature changes) in the steel girders and the concrete deck will create beneficial compressive stresses in the bridge deck (Krauss and Rogalla 1996). These advantages are lost if the maximum concrete temperature is not limited, as discussed in the previous section.

Design

Stresses in a bridge deck are affected by the amount of restraint induced by the girders. Restraint in a bridge deck can be represented by a restraint coefficient β, as shown in Eq. (1.4) (Ducret and Lebet 1997, Ducret et al. 1997).

$$\beta = \frac{A_g}{A_c} \tag{1.4}$$

where:

A_g = cross-sectional area of the steel girders

A_c = cross-sectional area of the concrete deck.

Increased restraint leads to increased residual tensile stresses in the concrete deck due to thermal hydration effects and a higher risk of early cracking (Ducret and Lebet 1997, Ducret et al. 1997). It is noted that the cross-sectional area of the deck is proportional to deck thickness, another design parameter.

The deck thickness can also affect thermal stresses in the deck. Increased volumes of concrete (in thicker decks) can lead to a build-up of the heat of hydration, higher peak temperatures, and earlier set times due to the reduced ability of the system to dissipate heat.

1.7.3 Recommendations to Control Thermal Effects

To reduce early heat of hydration effects, control can generally be exercised over the concrete material properties, curing construction practices, and implementation of temperature control. Krauss and Rogalla (1996) made the following recommendations to minimize the thermal effects for bridge decks:

- Use lower amounts of portland cement
- Use low heat of hydration portland cements and pozzolans
- Use minimum paste volumes
- Use larger-sized aggregates
- Use aggregates with low coefficients of expansion

- Avoid placement temperatures over 27ºC (80ºF); use ice to reduce concrete temperatures
- Cast concrete at temperatures at least 11ºC (20ºF) cooler than ambient air temperature
- Avoid casting in the morning and early afternoon. Use late afternoon or evening for casting
- Minimize solar radiation effects on bridge deck concrete during casting
- Specify bridge deck concrete based on 56- or 90-day compressive strengths to allow lower heat of hydration cementitious materials, including pozzolans, to be used

1.8 CONSTRUCTION

Construction methods have a significant effect on the amount of cracking in a bridge deck. Construction techniques can be used to reduce the amount and rate of shrinkage, thermal stresses, and thus reduce the risk of bridge deck cracking (Krauss and Rogalla 1996). The contractor responsible for the implementation of specifications during construction ultimately determines the quality of the bridge deck. Multiple studies report that cracking varies with contractor (Cheng and Johnston 1985, Krauss and Rogalla 1996, Lindquist et al. 2005). Good concreting practices should be specified and adhered to by the contractor (FHWA High Performance Concrete Technology Delivery Team 2005). Krauss and Rogalla (1996) report the construction related factors affecting cracking to be time of placement, weather conditions, curing method, length of curing, finishing procedures, and consolidation.

Evaporation is a key issue that affects shrinkage and cracking. If evaporation is not limited for both plastic and hardened concrete early in the life of the deck, cracking can result. Careful attention to placing, finishing, and curing practices can help minimize cracking (Rogalla et al. 1995). Construction methods that affect the evaporation of water from the deck include curing methods, time of construction, environmental conditions, fogging, placement method, texturing, and form type. Rapid evaporation can compound cracking problems already inherent to materials related shrinkage.

A discussion of how different construction practices affect cracking follows.

1.8.1 Weather and Environmental Conditions

Wind and high air temperatures together create severe evaporation conditions, although high evaporation rates can also occur during cold weather. Such conditions accelerate concrete surface drying and seriously increase the risk of plastic shrinkage cracking, and concrete should not be placed when such conditions exist (Krauss and Rogalla 1996). Evaporation should be measured at the jobsite. If weather conditions threaten high evaporation rates, practitioners often consider delaying placement as reasonable (Transportation Research Board 2006). Concrete containing silica fume or fly ash may exhibit increased susceptibility to plastic shrinkage cracking due to reduced rates of bleeding. Proper fogging and wet curing implemented immediately after concrete placement will minimize concrete surface exposure to drying conditions.

1.8.2 Temperature Control of Concrete During Construction

Construction practices can have significant effects on the thermal stresses and cracking in concrete bridge decks. Thermal stresses, as discussed in Section 1.7, are aggravated by higher concrete material temperatures at the time of placement, as well as warm air temperature and solar radiation. Reducing the concrete temperature during placement will reduce peak hydration temperatures and the resultant thermal stresses. Construction methods aimed at controlling the temperature of the concrete, such as using ice, chilled water, or liquid nitrogen, and wetting or shading aggregate piles should be used to limit the temperature of the plastic concrete at the time of placement. Krauss and Rogalla (1996) and Rogalla et al. (1995) recommend that when concrete is placed either during the day or when the air temperature is above 15ºC (60 ºF), the maximum concrete temperature should be at least 11ºC (20ºF) cooler than the air temperature. They also recommended that when concrete is placed in the evening or when the air temperature is below 15ºC (60 ºF), the concrete temperature should not exceed the air temperature. Retarders can be used to reduce temperature gain and the resulting thermal stresses. Retarders, however, can also increase the susceptibility of exposed concrete to plastic shrinkage cracking, so good curing practices are essential (Rogalla et al. 1995). Concrete continues to settle once finished, inducing planes of weakness as the concrete settles around the rigid reinforcing bars. Retarders increase the time the concrete has to settle before setting, thereby creating a more severe risk of settlement cracking.

The time of placement should be chosen to minimize the thermal stresses. Concrete should be placed so the weather immediately following placement will cool the concrete as it is hydrating and reaches peak hydration temperatures. Most bridge deck concrete, if placed in the late afternoon or early evening will reach the peak temperature during the night (Krauss and Rogalla 1996). The cooler air temperature and lack of solar radiation will reduce the peak hydration temperature and the risk of cracking (Krauss and Rogalla 1996). Placement during the late morning or early afternoon will most often maximize thermal stress and increase the risk of cracking.

1.8.3 Curing

Curing has significant influence over the properties of the bridge deck, including cracking, durability, strength, shrinkage, resistance to freezing and thawing, permeability, and abrasion resistance. Early initiation of effective wet curing can reduce cracking, while delayed wet curing increases cracking (Krauss and Rogalla 1996). Extended wet curing decreases the rate of early-age shrinkage and the total amount of shrinkage (Deshpande et al. 2007, Krauss and Rogalla 1996), thereby reducing restrained shrinkage cracking. Wet curing also helps to cool concrete during hydration and mitigate thermal stresses. Effective curing requires continuously maintaining moisture and temperature in the concrete sufficient to continue the hydration process and achieve the desired properties. Concrete protection at early ages is of prime importance. If the concrete dries out, even temporarily, hydration is stopped and is difficult to restart. Proper care at later ages does not compensate for a lack of protection at very early ages (Issa 1999). It is important to initiate curing as early as possible so as to prevent the exposed concrete surface from drying out. In the case of a bridge deck, immediate placement of wet curing material after strikeoff is ideal. Fogging can help to maintain an area of humidity directly above the surface of the concrete, but it is difficult to ensure complete protection of the entire surface with fogging. Therefore, direct contact wet curing should be placed as soon as possible.

The Transportation Research Board (2006) recommends immediate placement of pre-wetted burlap or cotton mats, not more than 10 or 15 minutes after the finishing machine is completed, while the FHWA's High Performance Concrete Designers' Guide (FHWA High Performance Concrete Technology Delivery Team 2005) recommends no more than 10 minutes after finishing. Contractor operations must be "tight" to achieve these time requirements. The 10-minute rule implies that curing materials be placed on plastic concrete before it has set, causing some owners and contractors concern over the appearance of the deck surface. Minor cosmetic damage to the deck surface is tolerable in exchange for an uncracked, durable, long-lasting deck (FHWA High Performance Concrete Technology Delivery Team 2005, Transportation Research Board 2006). Care can be taken to minimize surface indentations in the plastic concrete when placing curing material onto the deck. Also, saw-cutting grooves into hardened concrete after the curing is completed instead of tining the plastic concrete allows for the immediate placement of curing after finishing and ensures sufficient surface texturing.

Good curing practices are essential. Absorbent materials used for curing should be presaturated before placement. If dry materials are placed in direct contact with the concrete surface, they act as a wick, pulling moisture out of the concrete. Once presaturated materials are placed on the concrete surface, they must be maintained in the saturated condition. A constant water source should be provided, such as hand-held spray hoses, sprinkler systems or soaker hoses. The wet material, with a constant water source, should be covered with plastic sheeting securely placed so as to reduce moisture loss. Plastic sheeting alone should not be used for curing (Krauss and Rogalla 1996). It is important to ensure that no holes exist in the plastic sheeting and that the entire concrete surface is covered continuously. Close inspection of the curing should occur at regular intervals throughout the entire curing period. Ideally, wet curing should continue as long as possible to prevent cracking. Krauss and Rogalla (1996) recommend that wet curing be maintained for at least 14 days. After the wet curing period is completed, a curing compound can be applied to the concrete surface to slow the drying rate of the concrete (Krauss and Rogalla 1996, Transportation Research Board 2006).

1.8.4 Concrete Placement

Concrete placement on bridge decks today routinely involves pumping to place concrete on bridge decks. In the past, decks were placed using crane and buckets or by conveyors. Concrete mixtures that are pumped generally require higher cement paste contents than concretes placed by conveyors or buckets. Higher paste content leads to increased cracking (Darwin et al. 2004). Also, higher slump concretes associated with pumping may cause increased settlement cracking (Dakhil et al. 1975). It is not appropriate to choose or alter concrete mixtures by increasing cement, paste, or slump so as to utilize a more convenient placement method. Such practices increase cracking in bridge decks.

1.8.5 Consolidation

Proper vibration of all fresh concrete is essential to ensure adequate consolidation and prevent settlement cracking on bridge decks. Under-vibrated areas are prone to cracking (Rogalla et al. 1995). This is one of the basics of good concrete practice, yet it is often an overlooked facet of bridge deck construction (Transportation Research Board 2006). One or two hand vibrators are not generally adequate for bridge deck construction and construction personnel and inspectors generally pay little attention to proper vibration technique and thoroughness (Transportation Research Board 2006). The Kansas DOT requires the use of gang vibrators, mounted on a mechanical system at 0.3-m (1-ft) spacing to ensure uniform vibration of all bridge decks (Kansas Department of Transportation 1990a, Kansas Department of Transportation 1990b, Kansas Department of Transportation 2007a, Kansas Department of Transportation 2007b).

1.8.6 Concrete Finishing

Concrete finishing procedures can affect cracking. Increased cracking has been associated with delayed finishing and with hand finishing (Krauss and Rogalla 1996). The High Performance Concrete Structural Designer's Guide recommends that HPC be deposited, finished, and wet cured within 30 minutes (FHWA High Performance Concrete Technology Delivery Team 2005).

The properties of the concrete surface are important in crack initiation. A layer of cement paste (with no coarse aggregate) at the surface of the deck will aggravate evaporation rate problems and increase differential shrinkage throughout the cross section of the deck. Therefore, any construction method that causes a thicker layer of paste to be present at the surface of the deck should be avoided. Finishing techniques should produce a cross-section with the largest aggregate size fractions very close to the top surface of the deck. Construction practices previously included the use of vibrating screeds, whereas today double drum roller screeds are routinely used in the construction of bridge decks. Roller screeds work more paste to the surface than vibrating screeds (Darwin et al. 2004), increasing the risk of plastic shrinkage cracking.

If a fogging system is used after the screeding process, it is important to prevent the accumulation of water on the surface of the concrete from the fogging equipment (FHWA High Performance Concrete Technology Delivery Team 2005). Such water should not be used as a finishing aid to improve workability for the finishers as they perform final surface finishing. This will result in a surface with higher water content than the rest of the deck, and increases the risk of cracking.

Mechanical saw-cut grooving of the hardened concrete surface can produce more uniform and durable grooves than tining the fresh concrete surface (FHWA High Performance Concrete Technology Delivery Team 2005, Grady 1983, Krauss and Rogalla 1996). More importantly, immediate initiation of very early wet curing is possible, even before the concrete sets, so as to not allow any drying of the concrete surface, as discussed previously in the Section 1.8.3. A minor imprint of curing materials on the fresh concrete is not important compared to the problems caused by delayed application of curing. Saw-cut grooving eliminates the concern for damaging the tined surface. The prevention of cracking by immediate initiation of wet curing more than justifies the increased cost associated with saw-cut groove texturing.

1.8.7 Fogging

Continuous, proper fogging provides an area of high relative humidity directly above the surface of the finished concrete. This high humidity limits the rate of evaporation of water from the concrete. Effective fogging immediately after strikeoff can reduce plastic shrinkage cracking (Krauss and Rogalla 1996, Transportation Research Board 2006). Fogging nozzles should provide adequate vapor mist without allowing water to accumulate on the surface of the concrete (Transportation Research Board 2006). Exposed concrete should be continuously fogged following finishing until wet curing begins.

1.8.8 Formwork

The type of forms used for a bridge deck affects the exposure of the concrete to drying conditions. Stay-in-place forms keep the concrete surface at the underside of the deck from exposure to air and wind, while the top surface becomes exposed to drying conditions once wet curing is completed. This difference in boundary conditions initiates a moisture gradient throughout the deck cross section. Drying shrinkage through the deck cross section thus becomes linear rather than uniform, producing larger tensile stresses at the top surface of the deck and increasing the risk of deck cracking (Krauss and Rogalla 1996).

1.8.9 Drying

Drying of the bridge deck should only occur when the complete curing period has been completed. Slower drying reduces the probability of cracking. As stated in Section 1.8.3, the application of a curing compound when wet curing is terminated will reduce the rate of drying and the risk of cracking (Rogalla et al. 1995, Transportation Research Board 2006).

1.8.10 Planning and Inspection

Proper planning is essential for the successful construction of bridge decks with minimal cracking. The FHWA High Performance Concrete Structural Designers' Guide (FHWA High Performance Concrete Technology Delivery Team 2005) recommends a pre-placement meeting between the contractor, subcontractors, materials supplier and the engineer at least one week prior to any concrete placement. Such meetings should review all aspects of the construction specifications for the placement, including the concrete mix design, testing requirements, procedures for curing, finishing, placement, and provisions for hot or cold weather. A test of the finishing and vibration equipment prior to concrete placement is also recommended to ensure proper operation.

It is not uncommon in a construction environment for the specifications to not be properly implemented due to a lack of inspection and enforcement. Although they cannot ensure perfect compliance with the specifications, thorough inspection and strong enforcement of the construction methods, as outlined in clearly worded specifications, are critical to the successful implementation of any construction project aimed at minimizing cracking.

1.8.11 Cost

Some construction methods aimed at reducing cracking may increase initial construction costs while others may reduce costs. Maintenance and long-term costs, however, will be reduced if recommendations are implemented (Krauss and Rogalla 1996).

1.9 PREVIOUS WORK

1.9.1 Permeability

The Mechanism of Chloride Ingress

It is commonly recognized that diffusion is the primary mechanism for the transport of chloride ions through solid concrete in bridge decks. Some researchers note, however, that the cyclic nature of bridge deck exposure to wetting and drying and the application of chlorides may change the dominant mechanism from diffusion to capillary absorption, or sorption, with diffusion being a secondary transport mechanism. Comparing chloride ingress for cyclic and constant moisture exposure conditions in the laboratory, Miller and Miltenberger (2004) report that specimens that undergo cyclic wetting and drying exposure loading during ASTM C1556 bulk diffusion testing undergo deeper and greater total chloride ingress than specimens subject to constant moisture conditions. These specimens, presumably, undergo both diffusion and sorption, as compared to specimens that are exposed to constant surface concentration and are affected primarily by diffusion mechanisms.

Modeling

Fick's second law is commonly used to model chloride ingress into solid concrete by the mechanism of diffusion (Boulfiza et al. 2003, Detwiler et al. 1999, Lindquist et al. 2005, 2006, McGrath and Hooton 1999, Nokken et al. 2006, Suryavanshi et al. 2002, Tikalsky et al. 2005). This equation models one-dimensional flow for an uninterrupted concrete slab of infinite depth. In reality, test specimens and bridge deck slabs do not have infinite depth. Also, modeling has shown that the mere presence of reinforcing steel may significantly increase the rate of chloride diffusion and build-up at bar locations (Kranc et al. 2002).

Generally, the results of chloride profile analyses may be compared for different concretes. A chloride profile is prepared by plotting chloride concentration against the distance of the penetration below the surface of the specimen. A diffusion coefficient for each specimen may be estimated by mathematical analysis techniques fitting the measured chloride profile to a diffusion model (such as Fick's Second Law). These diffusion coefficients serve as a tool to compare the ability of different concretes to resist chloride ion penetration. Several mathematical analysis methods have been used by researchers to estimate the effective diffusion coefficient from chloride concentration profiles. Such methods include the least squares fit method, the Newton-Raphson method, the simplified linear error-function-based method (SLEM), and the graphical method (Suryavanshi et al. 2002). The least squares fit method of estimating diffusion coefficients by fitting the error function solution for Fick's Second Law of non-steady state ionic diffusion through a permeable material to the measured chloride profile is considered to be a reliable and repeatable method for comparing the performance of different concretes against chloride penetration (Suryavanshi et al. 2002). This method is commonly used by researchers for calculating the effective diffusion coefficient D_{eff} from measured chloride profiles (Fanous and Wu 2005, Kirkpatrick et al. 2002, Lindquist et al. 2005).

Equation (1.3) is a solution to Fick's second law for a constant diffusion coefficient and a constant surface chloride concentration. In reality, however, diffusion through concrete is not constant. The diffusion rate typically decreases with concrete maturity, continued hydration, and both physical and chemical chloride binding. Because diffusion is not, in reality, constant, the resultant constant coefficient from Eq. (1.3) is called an "effective" diffusion coefficient. Researchers have suggested other methods for modeling diffusion as nonconstant and dependent on time, temperature, both time and temperature, or surface chloride concentration (Hansen and Saouma 1999, Ji et al. 2005, Nokken et al. 2006). For the purpose of service life modeling, such nonconstant diffusion modeling methods may be of interest. It has been shown, however, that the resultant time-to-corrosion predictions vary widely depending on the method chosen (Nokken et al. 2006). This study does not purport to produce service life modeling results, therefore non-constant diffusion coefficient models are not used.

For long-term laboratory testing, specimens are exposed (by submersion or ponding) to a salt solution. In the case of actual bridge decks, salt is applied to the surface of actual bridge decks and the chloride levels at the surface fluctuate seasonally with rain, traffic and de-icing applications. Therefore, measured surface concentrations for bridge decks are typically defined as sampled at 13 mm (0.5 in.) below the surface of field bridge decks (Fanous and Wu 2005, Kirkpatrick et al. 2002, Weyers et al. 1994) to minimize these seasonal and weather fluctuation effects. Paulsson-Tralla and Silfwerbrand (2002) determined that the effective diffusion coefficient stabilized at approximately 15 mm (0.6 in.) below the surface of the concrete. Some researchers have suggested that surface chloride concentration levels increase over time, modeling the increase linearly (Berke and Hicks 1996) until reaching a maximum concentration when the concentrations become nearly constant (Ji et al. 2005, Phurkhao and Kassir 2005), increase linearly with square root of time, or with an exponential representation of surface chloride concentration with time (Kassir and Ghosn 2002). After analyzing several models including exponential, log, polynomial, and power functions, Weyers et al. (1994) determined that surface chloride concentrations increase for a short period of time (4 to 6 years), then fluctuate randomly about a mean value. Weyers et al., thus, concluded that assuming a constant surface chloride concentration for the purpose of computing effective diffusion coefficients is practical and realistic.

Although other solutions to Fick's second law with variable diffusion coefficients and variable surface concentrations have been proposed, this study

(Chapter 3) focuses on the constant diffusion coefficient and surface concentration model solution found in Eq. (1.3) because it is the one used most often in the literature. It is generally accepted that modeling chloride ingress with a constant diffusion coefficient and a surface concentration provides an effective tool for the purpose of comparing concrete materials.

Test Methods

AASHTO T 259 Resistance of Concrete to Chloride Ion Penetration (the 90-Day Ponding Test). The AASHTO T 259 test (2002, 1980) is a method for measuring a concrete's ability to resist chloride ion penetration. It consists of ponding a 3% sodium chloride solution on three cured and dried specimens (slabs) for 90 days. After ponding, samples are taken at depths throughout the cross section and the chloride concentration is determined for each sample. The depth of penetration and concentration is considered to be an indication of the concrete's ability to resist chloride ion penetration.

In this test method, the ponding cycle begins with the specimens in a dry condition. Thus, capillary absorption (sorption) may be an important mechanism of chloride ingress in addition to diffusion for this test. Specimens are not required to be sealed on the sides, so wicking may also have some influence on the transport mechanisms. McGrath and Hooton (1999) implemented a modified chloride ponding test in which the sides of cored samples from a specimen slab were sealed with epoxy before ponding to prevent wicking and the specimens were saturated to limit sorption over the first few days of ponding. Epoxy sealing the sides of a standard T 259 specimen can help prevent wicking. The extent of the wicking effect is not clear.

The sampling requirements of AASHTO T 259 include just two samples taken for chloride ion analysis, taken at the depth ranges of 1.6 mm (0.0625 in.) to 13 mm (0.5 in.), and from 13 mm (0.5 in.) to 25 mm (1.0 in.). This results in rather sparse sampling (2 samples) for the purpose of chloride profiling. Researchers have implemented precision profile grinding techniques in their sampling techniques for permeability testing (McGrath and Hooton 1999, Thomas 2006) to better characterize the chloride concentration profiles. For example, Detwiler et al. (1999) sampled at 1 mm (0.04 in.) increments from the ponded surface to a depth of 10 mm (0.4 in.), and then at wider intervals to a depth of approximately 70 mm (2.75 in.) (14 samples) for specimens ponded for 180 days.

AASHTO T 277 / ASTM C1202 Rapid Chloride Permeability Test (RCPT). The standard method of test for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration (2007), otherwise known as the Rapid Chloride Permeability Test (RCPT), is a widely used method for estimating a concrete's ability to resist chloride ingress. It consists of monitoring the amount of electrical current passed through a concrete core slice for six hours. A potential difference of 60 V dc is maintained across the ends of the specimen, one of which is immersed in a sodium chloride solution and the other in a sodium hydroxide solution. The total charge passed during the testing period is to be related to the resistance of the concrete to chloride ion penetration. Controversy exists over the use of this method for laboratory testing and acceptance purposes.

As described in Section 1.6, the technique was originally developed as a field test method, and the developers did not view the laboratory version of the test method as "an accurate, standard laboratory test to determine the absolute permeability of a given concrete" (Whiting and Mitchell 1992). Because the laboratory version of the test method was viewed as a rugged "fallback" when field testing was not feasible, no systematic investigation was conducted of the many variables that influence the adapted laboratory test. In 1992, the developers of the RCPT published a history of the development of the test method and warnings regarding the use of the RCPT for acceptance and quality control purposes and discussed the limitations of the test (Whiting and Mitchell 1992).

In the RCPT method, the charge passed (in coulombs) is used as an indicator of the permeability of the concrete. A table of coulomb values and the corresponding chloride penetrability is presented in the test method. Though this table is presented with a strong cautionary statement regarding its use for acceptance testing, it is widely used. The values in this table, in fact, originate from the results of a single core specimen taken from each of 12 concrete slabs, representing 12 types of concrete originally tested during the development of the field test for the FHWA (Whiting and Mitchell 1992). The table does not represent a large database of test results. The original report warns that these tabulated values do not include the effects of variables such as aggregate type, aggregate size, cement content, cement composition, and concrete density. The developers recommend that the user establish performance criteria correlations based on testing of local materials and warn that values in the table must be used with "extreme caution."

Acceptance of the RCPT is based on the assumption that proper correlations exist between the rapid test method and long-term test methods, such as the 90-day ponding test. Though it has been a subject of investigation since the 1970's, controversy still exists regarding whether proper correlations have been provided. ASTM C1202/AASHTO T 277 references several publications that provide examples of the interpretation and use of test results. Pfeifer, McDonald, and Krauss (1994) studied the results in these referenced documents and concluded that reliable and proper correlations had not been made. They also suggest that some RCPT results may prove to be misleading. For example, the RCPT may overestimate the protection provided by concrete with a high *w/cm* ratio containing mineral admixtures due to the inherently high electrical resistivity of these modified concretes. Similarily, portland cement only concrete with very low *w/cm* ratios, such as 0.30 to 0.32, may provide excellent protection to chloride ingress but can have high RCPT values, falsely indicating only moderate to poor levels of protection.

Concrete permeability is controlled mainly by the microstructure, including its porosity, pore-size, and tortuosity. The conductivity of hardened concrete is affected by many factors, such as moisture content, aggregates, degree of hydration, pore solution chemistry, microstructure, chemical admixtures, mineral admixtures, temperature, and pH (Liu and Beaudoin 2000).

A large temperature rise in the specimens is induced by the electrical current during testing. Temperature affects the rate of ion transfer in concrete. Electrical heating causes increased mobility of ions in the pore solution and, therefore, increases electrical conductivity, affecting the results of the RCP test. Originally developed as a field test in-situ, this was not expected to be a problem because a full scale bridge deck acts as a large thermal heat sink. The problem of temperature rise in laboratory specimens was not solved when AASHTO and ASTM test standardization occurred. Some researchers have proposed changes to the RCPT to include shorter testing periods so as to minimize the effect of temperature rise on the results (McGrath and Hooton 1999). Variations in the concrete, such as aggregate content and other factors that affect its thermal properties may also affect the heating characteristics of the material during testing.

There is concern regarding the use of RCPT for concrete with mineral admixtures such as silica fume. Silica fume changes the concrete's conductivity by altering the chemical composition of the pore solution. Diffusion of chlorides is dependant on the pore structure of the hardened concrete. RCPT measurements are affected by both the diffusion (pore structure) and the chemical composition of the pore solution. Because of this, Detwiler and Fapohunda (1993) suggest that it will be difficult to accurately use the method for concretes containing mineral admixtures. The inherent material conductivity change caused by the presence and different quantities of mineral admixtures may disproportionately affect (reduce) RCP values for concrete containing silica fume compared to the extent with which the material actually prevents chloride ingress (Shi et al. 1998). Thus, such results may exaggerate the apparent protection such materials provide against chloride ingress. It is, therefore, of particular importance to ensure proper handling of RCPT results for concretes containing silica fume and other mineral admixtures.

The precision and bias estimates found in AASHTO T 277/ASTM C1202, Section 13, for single-operator precision (35% variation in results from 2 tests) and multilaboratory precision (51% variation in results from 2 tests) are relatively high when compared with other accepted concrete testing methods to assess the quality of concrete. The developers note that significant improvements may be possible in the precision of the test. The developers also note that further work on statistically based acceptance limit definitions and improvement of precision are also necessary before the technique can be equitably applied as an acceptance tool (Whiting and Mitchell 1992).

Alternative Test Methods. Alternative electrical test methods to the T 277 test have been proposed. The Norwegian test method, discussed by Detwiler and Fapohunda (1993), measures chloride concentrations directly instead of electrical current passed. It uses a 12-V power source is used instead of a 60-V source, which reduces temperature increase. The method, however, requires a longer testing period than the T 277 method due to the lower voltage applied.

The NordTest NT-Build 492 (1999) is another chloride migration test that induces a DC voltage to one side of a saturated sample to drive chloride ions into the concrete sample. The test method was originally developed as the Rapid Migration Test (RMT) and was standardized as the NordTest NT-Build 492. The method calls for the sample to be split open afterward and sprayed with a silver nitrate solution to visually indicate depth of chloride penetration. The depth of penetration can be used to estimate a chloride diffusion coefficient using equations in the NordTest standard specification.

Liu and Beaudoin (2000) proposed a method based on a-c impedance techniques to provide faster testing with similar results to the T 277 test, while avoiding some of the problems with the T 277 method. Other researchers have proposed using concrete resistivity test methods as an indicator of concrete's ability to resist chloride ingress (Smith et al. 2004).

Materials & Construction Effects on Permeability

Silica Fume. The use of silica fume results in significant reductions in the effective diffusion coefficient for concrete exposed to chlorides. As silica fume content increases, the effective diffusion coefficient decreases (Detwiler et al. 1999). Most of the benefit of silica fume as it pertains to resisting chloride ingress, occurs from 0% to 6% replacement of cement by mass. Further increases in silica fume content appear to have little additional benefit.

Lightweight Aggregate. There is strong evidence in recent years that including prewetted lightweight aggregate in concrete mixtures can provide internal curing (Bentur et al. 2001, Bentz 2007, Bentz et al. 2005, Bentz and Snyder 1999, Kovler et al. 2004, Lura et al. 2006, Zhutovsky et al. 2002). Due to the high porosity and absorption of these materials, such as expanded slate, the LWA provides a reservoir of water that can efficiently supply water to hydrating cementitious materials internally, even after external surface curing regimes have been completed. When hydration lowers the relative humidity of the capillary pores in the hardened concrete, the water in the saturated lightweight aggregate migrates outwards into these capillaries (Neville 1997). This water is then available for continued hydration, mitigating autogenous shrinkage in the concrete. Current work at the University of Kansas has also shown that normal weight aggregates with high absorption values may also provide a similar "internal curing" effect. Lam and Hooton (2005) reported that using wet lightweight aggregate for internal curing produced concrete with higher strength and an interfacial transition zone (ITZ) that is less permeable (as tested by the RCPT method) than control mixtures. The increased porosity of LWA does however raise the question of whether the overall permeability of such concrete, as determined by a long-term test such as the 90-day ponding test, would be increased or decreased. Data from studies at the University of New Brunswick indicates that chloride penetration into concretes containing saturated lightweight aggregates is significantly reduced (Thomas 2006). The combination of mineral admixtures and internal curing via lightweight aggregate or other materials, may produce concrete with decreased diffusion coefficients as compared to concrete that receives only surface curing.

1.9.2 Thermal Stresses and Temperature Control of Concrete

Concrete Materials

Studies in Switzerland have demonstrated the effect of concrete hydration on the tensile stress in bridge decks. Implementing methods of cooling the concrete or using low-heat cementitious materials can significantly reduce the residual tensile stress in the deck due to the thermal effects of hydration and reduce the risk of cracking (Ducret and Lebet 1997, Ducret et al. 1997). By implementing such methods, peak concrete temperatures are reduced and temperature differentials between the deck and the girders are reduced. The compressive strain in the deck during the cooling process remains for longer periods of time and the net effect is that the final residual tensile strain, and thus tensile stress, is reduced.

Temperature rise in the deck can be between 15–30 ºC (59–86º F) during the first 12-15 hours after placement. In the absence of field measurements, the temperature rise in a deck can be assumed to be approximately 25ºC (77º F) during first 12-24 hours after placement (Ducret and Lebet 1997, Ducret et al. 1997) followed by a cooling period afterward of approximately 150 to 180 hours. Measurements in a study by Ducret and Lebet (1997) showed that the top flange of a steel girder is approximately the same temperature as the slab during hydration, while the bottom flange temperature nearly matched ambient temperatures.

The modulus of elasticity of the new concrete will increase with time. The modulus of elasticity during the first 12–15 hours can be assumed to be between 5–8 kN/mm^2 (725–1160 ksi), and 15–25 kN/mm^2 (2176–3626 ksi) during the cooling period (Ducret and Lebet 1997).

Numerical analysis and field measurements by Ducret and Lebet (1997) indicate that early-age cracking in bridge decks can be caused by thermal effects during the hydration process. Tensile stresses induced in the bridge deck can be high enough to cause early-age cracking, or the stress will remain in the deck as residual tensile stress, thus increasing the probability of future cracking during subsequent loading.

Construction Techniques

A University of Kansas study reported that crack density in bridge decks increases as air temperature range and maximum air temperature on the day of construction increases for overlay and monolithic bridge decks (Lindquist et al. 2005). Similarly, a Minnesota field study of cracking in bridge decks indicated that a wide range of ambient air temperatures on the day of deck casting may result in increased cracking (Eppers et al. 1998, French et al. 1999b). Babaei and Purvis (1996) also reported that environmental conditions during placement and curing of concrete decks can aggrevate cracking due to thermal effects.

There may be potential benefits to the idea of preheating cambered girders before casting the concrete deck (French et al. 1999b, Le et al. 1998).

Design

Ducret et. al. (1997) demonstrated the importance of the restraint coefficient β, as discussed previously in Section 1.7.2, on the residual tensile stresses in a deck due to concrete hydration thermal effects. Using measured values of strain in deck slabs during construction, they linked increased β with increased tensile stresses during the concrete hydration process. A simplified expression for the residual tensile stress in the concrete deck acting compositely with steel girders was derived based on the equilibrium of axial forces, the restraint coefficient β, the coefficient of thermal expansion of the concrete, and maximum temperature differentials between ambient air and concrete temperature in the deck during hydration, as well as the moduli of elasticity of the steel girders and the concrete at different ages during heating and cooling periods. The expression for the residual tensile stress (Ducret et al. 1997) is

$$\sigma_c = \frac{\alpha \times \beta^2 \times \Delta T \times E_s^{\ 2} \times (E_{c2} - E_{c1})}{(\beta \times E_s + E_{c2}) \times (\beta \times E_s + E_{c1})} \tag{1.5}$$

where:

σ_c = residual tensile stress in the concrete

α = coefficient of thermal expansion of the concrete

β = restraint coefficient defined by Eq. (1.4)

ΔT = maximum difference between ambient and concrete temperature during hydration

E_s = elastic modulus of steel

E_{c1} = mean elastic modulus of concrete during the heating period

E_{c2} = mean elastic modulus of concrete during the cooling period

In the absence of test data, assumed values for some of the parameters in Eq. (1.5) are suggested by Ducret et al. (1997).

A qualitative evaluation of the influence of β on the effects of concrete hydration and the risk of early cracking for a bridge deck was also presented by Ducret et al. (1997).

Krauss and Rogalla 1996. Krauss and Rogalla (1996) derived two systems of equations to analyze a composite bridge due to thermal and shrinkage effects. The first system assumed a constant, uniform temperature change throughout the deck and an independent uniform temperature change in the girders. The second system assumed a linear variation temperature change in the deck while maintaining the independent uniform temperature change in the girders. Analyses were run to calculate deck stresses for conditions of simply supported and continuous steel and concrete girders undergoing temperature changes of ±28ºC (±50ºF) and 100 and 500 με free-shrinkage for both systems of equations. They concluded that for many conditions, the thermal effects in the first 24 to 48 hours create enough tensile stresses to induce transverse cracking. Also, if the concrete does not crack during this time period, residual tensile stresses remain in the deck at or close to the tensile capacity of the concrete. Thus, when combined with the effects of shrinkage and additional temperature changes, the total stresses may exceed the strength of the concrete and induce cracking.

Babaei and Purvis 1996. Babaei and Purvis (1996) completed a study for the Pennsylvania Department of Transportation (PennDOT) investigating the causes and prevention strategies for cracking in bridge decks, aimed specifically at premature cracking in newly constructed bridge decks. The project was conducted in three phases. Phase 1 was an examination of existing bridge decks in Pennsylvania that were a maximum of 5 years old to determine the cause of cracking. "Walk-by" surveys were conducted on 111 bridges and in-depth studies of 12 bridges were completed with the goal of determining the causes and types of premature bridge deck cracking. The in-depth surveys included crack mapping, crack-width measurement, concrete coring, and pachometer surveys to locate bars and determine cover depth. Design and construction records were collected for these bridges. Analytical analysis of short-term (1–2 days) thermal shrinkage and long-term (112 days) drying shrinkage were completed to determine short and long-term shrinkage cracking thresholds. Bridge deck shrinkage, due to drying shrinkage and thermal effects was estimated by multiplying the number of transverse cracks in a span by an average crack width (0.01 in. based on the surveys) and dividing by the length of the span. Phase 2 included observation and field testing of eight bridge decks under construction. The goal was to identify field procedures contributing to shrinkage and cracking. Testing included measurement of concrete temperature for the first 8.5 hours after casting by insertion of a thermometer into the cast deck, air temperature, and ASTM C157/C878 free shrinkage testing of specimens cast with concrete sampled at the construction sites. Predictions of cracking and crack spacing were made based on calculations using the field test results. Comparison of cracking prediction calculations with field observations was completed. Phase 3 of the investigation included limited laboratory work focused on examining the effects of aggregate type, cement source and fly ash on shrinkage characteristics of concrete used in bridge deck applications. Concrete mixes were produced and tested for free shrinkage according to ASTM C157/C878 and also for temperature rise.

Transverse cracking was identified as the primary type of cracking, and simply-supported bridges seemed to have less cracking than continuous designs. Pachometer surveys and coring indicated that almost all transverse cracks were located directly above the top transverse bars. The cores revealed that cracks extended to the top reinforcement and beyond, and that cracks often intersected coarse aggregate particles, indicating that those cracks had occurred in or propagated into hardened concrete.

Calculations of cracking strain were based on using an "effective" modulus of elasticity to take the effect of creep into account by using a creep coefficient ν, the ratio of creep strain to instantaneous strain. A larger creep coefficient is used in calculations for longer-term loading during which creep increases the long-term strain. ACI 209 provides equations for the determination of a creep coefficient based on the loading duration and age of the concrete at the time of loading.

Findings of the analytical work concluded that thermal shrinkage of 228 με may initiate cracking in the first couple days (short-term) after placement. An ACI creep coefficient of 1.0 was used in the Babaei and Purvis (1995a) cracking calculations due to the short-term nature of the thermal loading. Drying shrinkage after curing, however, occurs over a longer period of time than thermal shrinkage, possibly over a year (Transportation Research Board 2006), allowing creep to help reduce tensile stress in the concrete deck. Using an ACI creep coefficient of 2.5, it was determined analytically that a residual long-term shrinkage of 400 με at 28 days (0.01% shrinkage) or 700 με at 112 days was needed to initiate cracking. These calculations were based on an assumed average crack width of 0.25 mm (0.01 in).

Total (long-term) concrete shrinkage strain is the accumulation of (short-term) residual thermal shrinkage strain e_R, and the (long-term) deck drying shrinkage strain e_D, as shown in Eq. (1.6).

$$e_T = e_D + e_R \tag{1.6}$$

where:

e_T = total long-term shrinkage strain, με

e_D = deck drying shrinkage strain, με

e_R = residual thermal shrinkage strain, με

If the initial thermal shrinkage strain is greater than the 228 με short-term cracking threshold, cracking can occur at early ages (while concrete is cooling down). If the initial thermal shrinkage strain is less than or equal to 228 με, it remains in the deck as residual shrinkage strain e_R. The effective thermal shrinkage strain is defined as any initial thermal shrinkage strain greater than the short-term cracking threshold (initial thermal shrinkage strain – 228 με). The effective long-term shrinkage strain is defined as any long-term shrinkage strain greater than the 400 με long-term cracking threshold (Total long-term shrinkage – 400 με).

The crack spacing is predicted assuming a crack width of 0.01 in.

$$D = \frac{10^6 \times 0.01 \text{ in.}}{\left(e_{eff} - C\right) \times 12 \frac{\text{in.}}{\text{ft}}} \tag{1.7}$$

where:

D = crack spacing, ft

e_{eff} = effective shrinkage strain, με

C = cracking threshold, με

Recommendations to minimize thermal shrinkage included maintaining the deck/girder temperature differential to a maximum of 11ºC (22ºF) for the first 24 hours after concrete placement. This corresponds with a thermal shrinkage strain of 150 με. Babaei and Purvis also recommended that, to limit crack spacing to a minimum of 9.1 m (30 ft), the maximum drying shrinkage, per ASTM C157, should be limited to 400 με at 28 days or 700 με at 112 days, as verified by a trial batch of the same concrete to be used on the bridge deck.

Babaei and Purvis recommend the use of retarders to reduce the concrete temperature rise, particularly in warmer weather. Retarders can, however, have a negative impact on settlement cracking. According to Babaei and Purvis (1996), wet curing with burlap should be initiated within 30 minutes after finishing and the burlap should be kept wet continuously. Also, in hot weather, casting at night will help to prevent heat build up. They further recommended that under cold weather conditions the deck should not be insulated unless the deck and girders are heated underneath as well. If the latter precaution is not implemented, the increased temperature differential between the girders and the concrete will cause increased thermal shrinkage strain and aggravate cracking. After the cold weather curing period is completed, the concrete temperature should be gradually lowered to the ambient temperature, with a maximum temperature drop of 3.9ºC (25ºF) every 24 hours. Heating can be slowly reduced and insulation can remain in place until the concrete temperature slowly reaches ambient temperatures.

1.9.3 Construction

Field Observations

Field observations of construction practices as they affect cracking are reviewed next.

Field construction observations during a study of cracking on Michigan bridge decks documented inadequate construction techniques (Aktan et al. 2003). Hand vibrator application was random and did not follow distinct patterns of application as required by the specifications and general enforcement of the time to curing specification was virtually nonexistent. Plastic concrete surfaces were left exposed and unprotected for extended periods of time, thus increasing the risk of cracking.

Babaei and Purvis (1996). As discussed in Section 1.9.2, Babaei and Purvis observed deck construction for the purpose of determining construction practices that could contribute to deck cracking. Delayed application of covering and curing in hot weather, leaving the finished concrete surface exposed to drying conditions for as long as three hours after placement, was identified as increasing the risk of plastic shrinkage cracking. Routine addition of water to the concrete truck after it left the batch plant was also noted. At one pour, they observed four of 13 trucks had water added to the mix, although it was not allowed by the specifications. Petrographic examination of cores taken from 5 of 12 bridges showed much higher water content than specified and reported in the field.

Babaei and Purvis (1995a) also observed that Pennsylvania DOT field personnel were not readily familiar with the format of the trip tickets and how they presented the mix design information, as well as the approved type and quantities of the mix ingredients for the project. They also noted that not all concrete trip tickets matched the specified quantities for the approved concrete mix design. One project was constructed with one half sack of cement more than the approved mix design, and for another project, water reducer was not used in the mix as designed. The researchers recommended introducing quality control procedures to monitor water content and other concrete ingredients from concrete batching to discharge.

Recommended Practices

Recommendations for specific construction practices to prevent cracking on bridge decks are outlined next.

Weather and Environmental Conditions. Krauss and Rogalla (1996) recommended many construction methods to reduce cracking in bridge decks. Concrete should not be placed on windy days, especially when the air temperature is hot or very cold. Decks should be placed during the early or mid-evening to reduce hydration temperatures and resulting thermal stresses. Placement during the late morning or early afternoon will most often maximize thermal stress and increase the risk of cracking. Krause and Rogalla suggested that if day placements are to be used, then extra longitudinal deck reinforcement should be added to resist the tensile thermal stresses and that solar radiation effects should be minimized during casting. The Transportation Research Board (2006) addresses this issue slightly differently. They suggest that decks be cast during the night or early morning hours so that decks and supporting girders experience temperature rise concurrently.

The evaporation rate should be measured at the job site, and wind breaks and sun shades should be used during periods of high evaporation. Utmost caution should be used when placing concrete in cold weather because of the risk for very high evaporation rates because of low relative humidity at the surface of the warm concrete.

Placement of decks during cold weather presents thermal challenges. Insulation of the deck during cold weather, while leaving girders exposed, can cause severe temperature gradients throughout the structure. The Transportation Research Board (2006) suggests using a complete “wrap around” enclosure of the deck and girders to provide heat retention to the girders, or at a minimum, draping tarps to help prevent wind from blowing under the structure. Babaei and Purvis recommend limiting the deck/girder temperature differential to a maximum of 12ºC (22ºF) for 24 hours after casting.

Temperature Control of Concrete During Construction. Krauss and Rogalla (1996) recommend that plastic concrete temperature should be 5ºC (10ºF) to 10ºC (20ºF) cooler than ambient temperature. If the ambient temperature is below 16ºC (60ºF), then the concrete temperature should be limited to ambient temperature. This often means cooling the concrete. They suggest shading aggregate piles or using ice as a portion of the mix water.

Researchers have reported that limiting concrete temperature at the time of placement can dramatically reduce the risk of cracking (Babaei and Purvis 1995a, Ducret and Lebet 1997, Krauss and Rogalla 1996, Lebet and Ducret 2000). Heat of hydration and thus tensile thermal stresses are reduced by cooling the concrete. Lebet and Ducret (2000) suggest using low heat cement, liquid nitrogen, or cooling pipes as effective methods to limit peak hydration temperatures, lengthen the time to reach peak temperatures, and limit the thermal stresses in a deck.

Curing. Krause and Rogalla outline vigorous curing practice recommendations. Curing must be implemented as soon as possible. Curing can include misting, application of curing compound, and use of wet blankets. Wet curing should begin as soon as possible after finishing. Prewetted saturated coverings such as wet burlap should be used as curing material. Constant moisture should be maintained. Ice should be used to reduce the temperature of the plastic concrete to 27ºC (80ºF) or lower. Fogging and windbreaks should be used when the evaporation rate exceeds 1 kg/m^2/hr (0.2 lb/ft^2/hr) for normal concretes. Fogging and evaporation retarder films should be used immediately following screeding.

Ideally, wet curing should continue as long as possible to prevent cracking. Studies at the University of Kansas (Deshpande et al. 2007) have shown that extending curing time reduces concrete shrinkage. Krauss and Rogalla (1996) recommend that wet curing be maintained for 14 days. Whiting, Detwiler and Lagergren (2000) recommended a minimum curing time of seven days to reduced the cracking tendency of concrete containing silica fume. Frosch, Radabaugh, and Blackman (2002) recommend a minimum of seven days wet curing on all bridge decks. Longer curing reduces both shrinkage (Deshpande et al. 2007) and the depth of chloride penetration through solid concrete when tested with standardized methods (Hooton et al. 2002).

After the curing period has been completed, a curing compound can be applied to the concrete surface to slow the drying rate of the concrete (Transportation Research Board 2006). Curing compound has been used after moist curing of HPC concrete overlays in Virginia (Sprinkel and Ozyildirim 1998).

Concrete Placement. Pumping concrete for bridge deck construction typically causes a drop in the entrained air content of approximately 1%. Contractors typically furnish concrete with extra air to compensate for the air loss during pumping (Yazdani et al. 2000). For a construction job, it is therefore necessary to clarify concrete testing procedures (before the pump vs. after the pump) and acceptance requirements.

Consolidation. For all bridge deck construction, the Kansas DOT requires the use of internal gang vibrators mounted on a mechanical system at 0.3 m (1 ft) spacing to ensure uniform vibration of the entire bridge deck (Kansas Department of

Transportation 1990a, Kansas Department of Transportation 1990b, Kansas Department of Transportation 2007a, Kansas Department of Transportation 2007b).

Fogging. Studies in Kansas have shown that efforts to reduce evaporation during construction have resulted in reduced cracking in bridge decks (Darwin et al. 2004).

Concrete Finishing and Texturing. The Transportation Research Board (2006) recommends minimizing hand finishing and generally discourages the use of bullfloats because excessive finishing can delay placement of curing and can also lead to future scaling problems.

A New York State study (Grady 1983) compared sawed-groove texturing of hardened concrete to tining of the plastic concrete for bridge deck construction. Tests showed that sawed-groove texturing did not affect scaling or small-scale fracturing of the concrete and provided a deep and durable frictional riding surface. Grady also concluded that sawed-groove texturing did not increase the chloride penetration at depths of 25 mm (½ in.) or deeper.

Formwork. Researchers at Purdue University instrumented a continuous steel girder bridge and concrete deck with stay-in-place forms to investigate stresses experienced by the deck reinforcement (Frosch et al. 2002). They concluded that stay-in-place forms contributed to transverse deck cracking by preventing moisture loss at the bottom surface and creating a shrinkage gradient through the depth of the deck.

Krauss and Rogalla's (1996) analytical study found that stay-in-place forms create non-uniform shrinkage and increase tensile stresses in bridge decks that can lead to cracking.

Pouring Sequence. There are conflicting reports on the effect of casting sequence on cracking in bridge decks. Analysis performed by Lebet and Ducret (2000) report that a "piano method" casting sequence (concreting the span zones prior to the support zones) can significantly decrease tensile stresses in the deck as compared to a continuous casting method. Issa (1999) reported that various sequences of pours resulted in significant differences in curvature. This and reported cracking of continuous decks at the support regions lead him to conclude that further analysis of pouring sequence is justified. Reports from North Carolina recommend alternating casting sequences (Cheng and Johnston 1985). However, other researchers have reported that casting sequence has minimal effect on total bridge deck cracking (Krauss and Rogalla 1996, Lindquist et al. 2005).

Other Practices. Researchers in Minnesota (French et al. 1999a) recommended studying the potential beneficial effects of preheating cambered steel girders prior to casting of the concrete deck to reduce tensile stresses in the deck.

1.10 OBJECTIVE AND SCOPE

Many analytical and field studies have identified the principle causes of bridge deck cracking. Materials, construction methods, and design parameters have been identified as affecting cracking and recommendations to minimize cracking in bridge decks have been outlined. Few studies, however, have implemented the findings to construct bridge decks with minimal cracking. This study is part of an ongoing investigation aimed at implementing current best practices in materials and construction practices to build 20 Low-Cracking High-Performance Concrete (LC-HPC) bridge decks with minimal cracking.

This report reviews construction practices and outlines construction specifications as they pertain to cracking on bridge decks, including curing methods, temperature control of concrete, placement and finishing techniques, fogging, consolidation, and inspection. Results of the construction experiences for 14 LC-HPC and 14 Control bridge decks and the preliminary crack surveys for the first 7 LC-HPC and 7 Control bridge decks built in Kansas are reported. Crack survey results are compared with Control structures built using standard specifications.

For bridge deck concrete that is uncracked, it is important to provide adequate protection against chloride migration to the reinforcing steel. AASHTO T 259 ponding tests are conducted to evaluate concrete mixtures designed for low-cracking characteristics. Effective diffusion coefficients are determined.

Chapter 2

EXPERIMENTAL METHODS

2.1 GENERAL

The purpose of developing low-cracking high-performance concrete (LC-HPC) for use in bridge deck construction is to minimize cracking to prevent premature deterioration of the deck. Cracks allow water and chlorides direct access to the reinforcing steel, accelerating corrosion of the reinforcing steel and freeze-thaw damage associated with water penetrating the cracked concrete. In addition to low-cracking, it is also important to limit the ingress of chlorides through solid concrete. Procedures for measuring concrete permeability are needed to compare performance and evaluate mixtures for use on bridge decks. Once bridge decks are constructed, a repeatable method of quantifying the amount of cracking in bridge decks is needed to evaluate materials and construction parameters in the field.

The experimental methods used for the laboratory investigation of the permeability of LC-HPC concrete and for the field investigation of the performance of LC-HPC bridge decks and the corresponding control decks are described in this chapter. The chapter covers the materials, equipment, procedures for the laboratory work, and the techniques used for performing crack surveys and crack density calculations.

2.2 MATERIALS AND APPARATUS FOR PERMEABILITY TESTS

This section describes the materials and apparatus used for the AASHTO T 259 permeability test used to evaluate the LC-HPC concretes developed in this study.

2.2.1 Cement

The cement used in this study was Type I/II portland cement (meets the ASTM C150 specification for both Type I normal portland cement and Type II modified portland cement) and Type II portland cement manufactured specifically as ground more coarsely than standard cements today. The Type I/II cement was obtained in five samples over a period of 3½ years. The Type II cement was obtained in two samples over two calendar years. The cement was analyzed by the Ash Grove Cement Company Technical Center in Overland Park, Kansas. Tests included X-Ray Fluorescence (XRF) elemental analysis, followed by a Bogue analysis based on the elemental analysis results. X-Ray Diffraction (XRD) mineralogical analysis and Particle Size Distribution (PSD) laser particle size analysis were preformed for most of the specimens. Blaine fineness was determined using ASTM C204 "Test Method for Fineness of Hydraulic Cement by Air Permeability Apparatus." The specific gravity of the cements used in this study was either 3.15 or 3.2. The Blaine fineness ranged from 3600 to 3816 cm^2/g for the Type I/II cements and from 3060 to 3351 cm^2/g for the Type II cements. The physical properties and chemical composition of the cements used in this study are shown in Tables 2.1(a) and 2.1(b).

Typical Blaine fineness values for standard Type I cements used today are commonly in the range of 3500 – 4000 cm^2/g, whereas values for coarse ground cement can be in the range of 2800 – 3200 cm^2/g. The latter is produced only in small quantities and is not widely available. The Blaine fineness of Type II sample 1 is within the range for coarse ground cement. However, sample 2 falls between the two ranges and, therefore, is termed "medium ground."

Table 2.1(a) Portland cement Type I/II chemical composition information

	Percentages by Weight				
	Portland Cement Type I/II				
Sample No.	1	2	3	4	5
XRF:					
SiO_3	21.45	21.04	21.23	21.69	20.88
Al_2O_3	4.68	4.81	4.69	4.92	4.85
Fe_2O_3	3.55	3.25	3.56	3.38	3.42
CaO	63.28	63.24	63.31	61.91	62.91
MgO	1.57	2.00	1.69	1.7	1.92
SO_3	2.66	2.77	2.76	3.1	2.79
Na_2O	0.19	0.23	0.22	0.24	0.21
K_2O	0.54	0.46	0.53	0.46	0.52
TiO_2	0.26	0.29	0.28	0.32	0.30
P_2O_5	0.08	0.10	0.09	0.10	0.10
Mn_2O_3	0.13	0.10	0.13	0.10	0.11
SrO	0.17	0.19	0.17	0.15	0.20
Loss on Ignition (LOI)	1.47	1.40	1.39	1.67	1.99
Total	100.03	99.88	100.06	99.74	100.20
Alkali Equivalent (EQV)	0.54	0.53	0.57	0.54	0.55
Bogue Analysis:					
C_3S	50	53	52	37	47
C_2S	23	21	22	34	24
C_3A	6	7	6	7	7
C_4AF	11	10	11	10	10
Testing Report Date	9/12/2005	9/12/2005	9/12/2005	7/16/2007	7/16/2007
Manufacturer	AG[1]	AG[1]	AG[1]	AG[1]	AG[1]
Specific Gravity	3.2	3.15	3.15	3.2	3.2
Blaine Fineness, cm^3/g	3816	3674	3804	3600	3730
Batch Numbers	131 146 133 148 139 161 141	234 235	239	328 347 330 351 334 354 335 355 338 358	378 387 380 388 381 424 385

AG[1] = Ash Grove Cement Company plant in Chanute, KS
AG[2] = Ash Grove Cement Company plant in Seattle, WA
LF[3] = Lafarge North America plant in Seattle, WA

Table 2.1(b) Portland cement Type II chemical composition information

	Percentages by Weight		
	Portland Cement Type		
Sample No.	1	2(a)	2(b)
XRF:			
SiO_3	20.76	20.85	20.83
Al_2O_3	4.78	4.79	4.80
Fe_2O_3	2.94	3.58	3.57
CaO	64.55	65.00	64.69
MgO	2.11	1.18	1.19
SO_3	2.52	1.44	2.25
Na_2O	0.41	0.50	0.51
K_2O	0.17	0.16	0.17
TiO_2	0.59	0.24	0.25
P_2O_5	0.11	0.07	0.07
Mn_2O_3	0.08	0.09	0.09
SrO	0.13	0.14	0.14
Loss on Ignition (LOI)	1.32	1.67	1.46
Total	100.46	99.73	100.03
Alkali Equivalent (EQV)	0.42	0.60	0.62
Bogue Analysis:			
C_3S	62	65	61
C_2S	13	11	13
C_3A	8	7	7
C_4AF	9	11	11
Testing Report Date	3/31/2004	9/12/2005	9/12/2005
Manufacturer	AG[2]	LF[3]	LF[3]
Specific Gravity	3.2	3.2	3.2
Blaine Fineness, cm^3/g	3060	3351	3329
Batch Numbers	144 164	240 244 246	

AG[1] = Ash Grove Cement Company plant in Chanute, KS
AG[2] = Ash Grove Cement Company plant in Seattle, WA
LF[3] = Lafarge North America plant in Seattle, WA

2.2.2 Fine Aggregates

Kansas River sand and pea gravel were used as fine aggregates for all concrete. The material was obtained over a period of 2½ years in four samples of Kansas River sand and six samples of pea gravel. The Kansas River sand was KDOT approved and had an average specific gravity of 2.63 and an absorption of 0.35%. The pea gravel had an average specific gravity of 2.62 and an absorption of 0.6%. Gradations for the sand and pea gravel are shown in Tables 2.2 and 2.3.

Table 2.2 KDOT approved Kansas River sand gradations

Sieve	Percent Retained			
Sample No.	1	2	3	4
4.75-mm (No. 4)	1.6	0.9	1.4	0.8
2.36-mm (No. 8)	12.7	10.0	10.0	10.5
1.18-mm (No. 16)	20.9	18.9	18.0	19.6
600-µm (No. 30)	25.4	25.7	25.3	24.5
300-µm (No. 50)	29.5	27.5	30.2	28.0
150-µm (No. 100)	8.6	13.3	12.6	12.6
75-µm (No. 200)	1.0	3.1	1.8	3.5
Pan	0.2	0.6	0.9	0.6

Table 2.3 Pea gravel gradations

Sieve	Percent Retained					
Sample No.	A	B	C	2	5	6
4.75-mm (No. 4)	12.5	10.1	9.5	9.3	11.4	8.4
2.36-mm (No. 8)	40.5	46.6	40.9	31.2	38.6	38.7
1.18-mm (No. 16)	30.2	28.3	35.2	31.4	28.4	30.2
600-µm (No. 30)	9	8.8	8.8	12.6	11.7	12.0
300-µm (No. 50)	5.6	3.8	3.4	9.3	6.9	7.4
150-µm (No. 100)	1.7	1.5	1.3	4.9	2.1	2.5
75-µm (No. 200)	0.4	0.3	0.3	0.9	0.4	0.4
Pan	0.2	0.4	0.6	0.4	0.6	0.5

2.2.3 Coarse Aggregates

The coarse aggregate used in this study was Kansas DOT approved Class I limestone with an average specific gravity of 2.58 and an absorption of 2.8 to 3.0%.

The coarse aggregate was obtained in seven samples over a 2½ year period. Coarse aggregate gradations are shown in Table 2.4.

Table 2.4 KDOT Class I limestone gradations

Sieve	Percent Retained					
Sample No.	A	B	C	D	D(a)	D(b)
37.5-mm (1 1/2-in.)	0	0	0	0	0	0
25.0-mm (1-in.)	0.1	0.1	0	0	0	0
19.0-mm (3/4-in.)	0.1	0.1	0	0.1	0.1	0
12.5-mm (1/2-in.)	11.3	11.3	25.0	21.7	44.7	0
9.5-mm (3/8-in.)	18.7	18.7	29.5	24.1	49.6	0
4.75-mm (No. 4)	48.7	48.7	35.2	41.0	0	80.2
2.36-mm (No. 8)	15.1	15.1	5.6	7.4	0	14.5
Pan	6.1	6.1	4.3	5.4	5.6	5.3

Table 2.4 (con't) KDOT Class I limestone gradations

Sieve	Percent Retained					
Sample No.	3	3(a)	3(b)	4	4(a)	4(b)
37.5-mm (1 1/2-in.)	0	0	0	0	0	0
25.0-mm (1-in.)	0	0	0	0	0	0
19.0-mm (3/4-in.)	0	0	0	0	0	0
12.5-mm (1/2-in.)	20.8	42.2	0	22.0	42.3	0
9.5-mm (3/8-in.)	28.6	57.8	0	30.1	57.7	0
4.75-mm (No. 4)	42.4	0	83.8	41.4	0	89.6
2.36-mm (No. 8)	6.0	0	11.8	3.1	0	6.7
Pan	2.3	0	4.5	3.5	0	3.8

Table 2.4 (con't) KDOT Class I limestone gradations

Sieve	Percent Retained		
Sample No.	5	5(a)	5(b)
37.5-mm (1 1/2-in.)	0	0	0
25.0-mm (1-in.)	0	0	0
19.0-mm (3/4-in.)	0	0	0
12.5-mm (1/2-in.)	27.4	45.6	0
9.5-mm (3/8-in.)	32.2	53.6	0
4.75-mm (No. 4)	35.7	0	89.5
2.36-mm (No. 8)	2.5	0	6.4
Pan	2.1	0.8	4.2

2.2.4 Mineral Admixtures

Mineral admixtures used included two samples of Grade 100 ground granulated blast furnace slag (GGBFS) and one sample each of Grade 120 GGBFS and silica fume. The chemical composition, manufacturer, and specific gravity of each mineral admixture used in this study are shown in Table 2.5.

Table 2.5 Mineral admixture chemical composition and production information

	Percentages by Weight			
Material	GGBFS			Silica Fume
	Grade 100		Grade 120	
Sample No.	1	2	1	1
XRF:				
SiO_3	36.35	43.36	38.28	94.49
Al_2O_3	9.64	8.61	10.69	0.07
Fe_2O_3	0.88	0.37	0.49	0.10
CaO	39.92	31.13	35.35	0.53
MgO	9.17	12.50	10.68	0.62
SO_3	2.21	2.24	2.85	0.11
Na_2O	0.23	0.21	0.27	0.09
K_2O	0.44	0.40	0.37	0.54
TiO_2	0.50	0.32	0.44	ND
P_2O_5	0.02	ND	0.01	0.07
Mn_2O_3	0.40	0.35	0.34	0.02
SrO	0.07	0.04	0.05	0.01
Cl^-	NT	ND	0.09	0.05
Loss on Ignition (LOI)	0.00	0.37	0.00	3.21
Total	99.83	99.90	99.91	99.90
Alkali Equivalent (EQV)	0.52	0.47	0.51	0.45
Testing Report Date	4/13/2006	7/16/2007	7/16/2007	7/16/2007
Manufacturer	Holcim[1]	Holcim[1]	LF[2]	Euclid[3]
Specific Gravity	2.86	2.86	2.90	2.20
Batch Numbers	328	378	347	354
			351	355
			354	358
			355	378
			358	380
			424	381

Holcim[1] = GranCem® produced by Holcim Inc.
LF[2] = NewCem® produced by Lafarge North America
Euclid[3] = Eucon MSA produced by Euclid Chemical Company

2.2.5 Chemical Admixtures

Plasticizing admixtures, air-entraining agents, and shrinkage reducing admixtures manufactured by BASF Construction Chemicals, LLC, and Grace Construction Products were used in the study. Manufacturers were consulted to ensure admixture compatibility, and admixtures from the two companies were not used in the same batch. The chemical admixtures used in each batch are included in the mix proportion tables in Appendix A.

Plasticizing Admixtures

Glenium® 3000 NS, produced by BASF Construction Chemicals, LLC, was the plasticizing admixture used for most mixtures. Glenium® 3000 NS is a carboxylated polyether based plasticizer that meets the ASTM C494 requirements as both a Type A and a Type F admixture. The solids content is 30%, and the specific gravity ranges from 1.08 to 1.1.

Adva® 100, produced by Grace Construction Products, was used for some of the concrete mixtures. It is a carboxylated polyether based plasticizer that meets the ASTM C494 requirements as a Type F admixture. The solids content ranges from 27.5% to 32.5%, and the specific gravity ranges from 1.02 to 1.12.

Air-Entraining Agent (AEA)

Micro Air®, produced by BASF Construction Chemicals, LLC, was the air-entraining agent used for most mixtures. The solids content is 13%, and the specific gravity is 1.01.

Daravair® 1000, produced by Grace Construction Products, was used as the air-entraining agent for some of the concrete mixtures. The solids content ranges from 4.5% to 6.0%, and the specific gravity ranges from 1.00 to 1.04.

Shrinkage Reducing Admixture (SRA)

Tetraguard® AS20, produced by BASF Construction Chemicals, LLC, was the shrinkage reducing admixture (SRA) used in this study. Tetraguard® AS20 is a polyoxyalkylene alkyl ether. It is an organic liquid and, therefore, has no solids content. The specific gravity is 0.99 (8.21 lb/gal), and the admixture is used on an exact weight basis replacement for water. In 2003, the manufacturer's recommended dosage was 1.0% to 2.5% by mass of cementitious material. By 2006, the manufacturers recommended dosage had been lowered to 0.7% to 2.0%, presumably due to difficulty in maintaining entrained air content at the higher dosage levels.

2.2.6 Mixing Equipment

Concrete was mixed in the laboratory using a Lancaster counter-current rapid batch mixer. For batches larger than 0.050 m^3 (0.065 yd^3), a Stone 95CM concrete drum mixer with 0.25 m^3 (9 ft^3) capacity was used.

2.2.7 Sandblasting Equipment

Specimens were abraded by sandblasting with a Cyclone PBH 1000 sandblasting cabinet system using a Cyclone 5 CFM Tungsten carbide nozzle. An aggressive black silicon carbide 120 grit was used to facilitate abrasion of the concrete surfaces. Regular maintenance of the sandblasting cabinet system, including rotation of the air jet and replacement of worn parts, was vital to ensure proper functioning. Items replaced regularly included the nozzle, gun assembly, the air jet, and the grit.

2.2.8 Coring Equipment

Specimens were wet-cored using a Milwaukee diamond-core drilling rig and motor. A 75-mm (3-in.) Milwaukee heavy-duty premium diamond core bit was used.

2.2.9 Grinding Equipment

Precision sampling of specimens was completed using an Enco 305×914 mm (12×36 in.) bench lathe with Enco 9.5-mm (3/8-in.) Style D carbide tipped tool bits. A new bit or a newly sharpened bit was used for sampling each specimen. Bits were hand-machined after use to maintain a sharp cutting edge.

2.2.10 Electrode probe

Chloride testing, as described in Section 2.5, was completed using an Orion 96-17 Ionplus® Sure-Flow® combination chloride electrode probe.

2.3 LABORATORY METHODS

Laboratory methods for mixing, casting, curing, drying, abrading by sandblasting, and precision sampling by lathe of the permeability specimens are described in this section.

2.3.1 Mixing Procedure

The concrete mixing procedure was adapted from the Silica Fume Association recommendations for making silica fume concrete in a laboratory mixer (Holland 2005).

All concrete in this study was mixed in accordance with this procedure. The coarse aggregate was batched in the saturated surface-dry (SSD) condition, while the mix water was adjusted to account for deviations from the SSD condition for the other aggregates.

Prior to mixing, the mixer surface was dampened, the coarse aggregate was placed in the mixer, and 80% of the water was added. Silica fume, if used, was added slowly into the revolving mixer containing these materials and mixed for 1½ minutes. Cement and slag, if used, were added slowly into the revolving mixer and mixed for 1½ minutes. The fine aggregate was then added. The plasticizing admixture combined with 10% of the water was added and mixed for 1 minute. The air-entraining admixture combined with 10% of the water was added and mixed for 1 minute. If used, the shrinkage reducing admixture (SRA) was added. Mixing continued for 5 minutes, followed by a 5 minute rest period. During rest periods, the concrete temperature was checked and the concrete was covered with dampened towels or plastic sheeting to prevent evaporation. After the rest period, the concrete was mixed for an additional 3 minutes. If the concrete contained an SRA, a 30-minute rest period was observed to allow the air content to stabilize. After the 30 minute rest period, the concrete was mixed for 1 minute.

The temperature of the concrete was maintained between specified limits reported in Section 2.7. Concrete was cooled by adding liquid nitrogen during the 5-minute mixing period. Temperature was checked during the 3-minute resting period and additional liquid nitrogen was added during the final mixing period as necessary.

2.3.2 Casting

Concrete batches were tested slump, temperature, and air content in accordance with ASTM C143, C1064, and C173 (Volumetric Method), respectively.

The AASHTO T 259 permeability specimens were 12×12×3 in., with a ¾ in. dam cast integrally with the specimen. The specimens were cast upside down in molds constructed from ¾ in. plywood. The specimens were cast in two layers using a vibration table with amplitude 0.15 mm (0.006 in.) and a frequency of 60 Hz. Specimens were vibrated for a minimum of 30 seconds and maximum of 60 seconds per layer until entrapped air bubbles were removed. Excess concrete was removed by screeding with a 4×1 wooden board during vibration. Molds were externally cleaned with damp sponge to remove excess concrete.

2.3.3 Curing

The AASHTO T 259 specimens were placed on top of two 1× or 2× boards of equal thickness to facilitate handling. Freshly cast specimens were immediately covered with one sheet of 150 µm (6 mil) wet mylar sheeting and one layer of 90 µm (3.5 mil) plastic sheeting, secured around the form with a large rubber band. A 9.5

mm (0.375 in.) plexiglass plate was then placed on top of the specimen and another layer of plastic sheeting placed on top with the edges tucked under the edges of the form. Specimens remained in an air conditioned laboratory, undisturbed for 24 hours. Specimens were demolded at 24 ± 1 hr and cured in lime-saturated water at 23 ± 0.5°C (73 ± 1°F). The curing period is as noted in the testing program.

2.3.4 Drying

After the wet curing period was completed, specimens were dried in an environmentally controlled room at 23 ± 2°C (73 ± 3°F) and a relative humidity of 50 ± 4 percent in accordance with AASHTO T 259, as described in Section 2.4.

2.3.5 Procedure for Abrasion by Sandblasting

Abrasion by sandblasting was performed for each specimen used for the AASHTO T 259 90-Day Ponding Test, described in Section 2.4. The goal of this procedure is to uniformly abrade the entire surface of the specimen for a specified period and to visually match a prototype specimen for the amount of abrasion.

Specimens were marked using a permanent black Sharpie marker with a grid, as shown in Fig. 2.1. The specimens were abraded by sandblasting for 30 minutes of effective contact. Effective contact is defined as abrasion of the concrete surface by sandblasting while the user can identify sparks from the grit contacting the concrete surface. For the sandblasting equipment used in this study, effective contact was indicated by sparks, appearing as a bright white spot, on the surface of the concrete even when vision was impaired through the viewing window. Plastic guard shields were typically replaced on the viewing window after every two specimens or as needed. Regular maintenance of the sandblasting equipment, as described in Section 2.2.7, is necessary for proper functioning and effective contact.

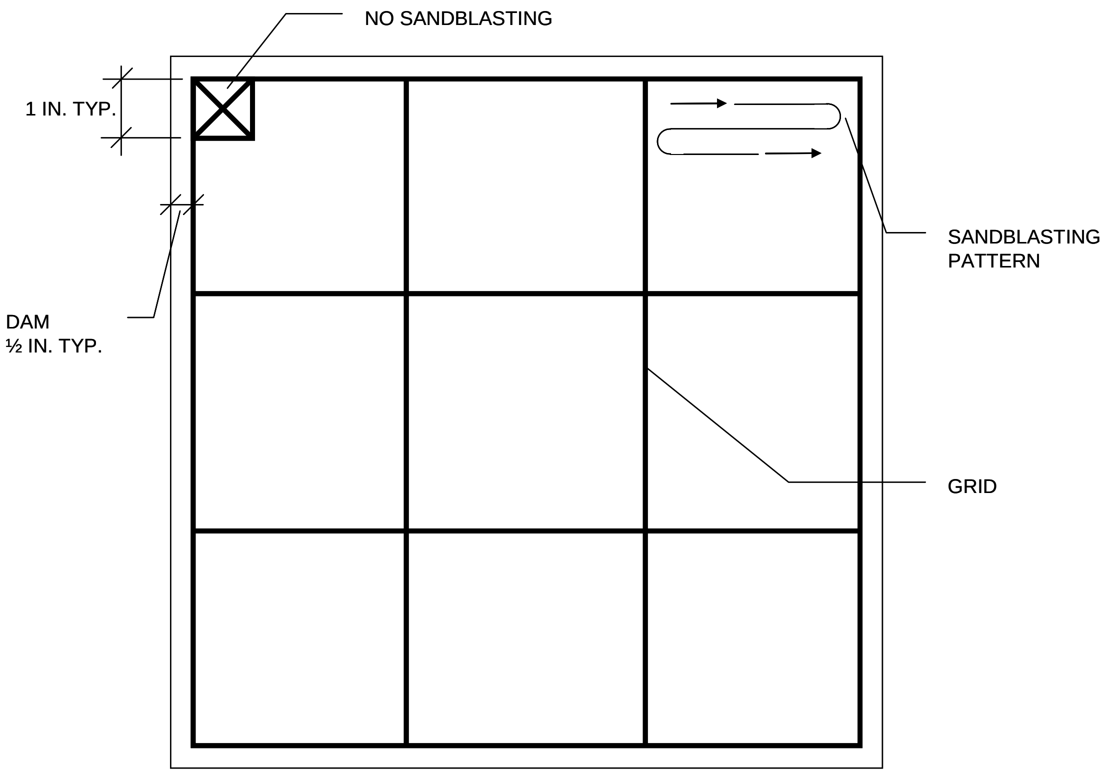


Figure 2.1 Specimen marking and sandblasting pattern.

The specimen surfaces were systematically abraded in a pattern, as shown in Fig. 2.1, until the entire surface of the specimen was abraded while keeping track of effective contact time. The gun was moved fast enough so that the concrete was not grooved by the sandblasting. The time it took to complete one pass of the specimen was dependant on the speed the user moved the sandblasting gun. Typically, a complete pass of a specimen took between 10 to 15 minutes. Sandblasting removed the grid pattern marked on the surface. A 25-mm (1-in.) reference square in one corner (Fig. 2.1) was not sandblasted.

After each complete pass of the specimen, the specimen was checked for uniformity of abrasion. Missed areas were blasted in a random pattern while keeping track of the blasting time.

The specimen was remarked with the grid pattern and another complete pass of the specimen was completed, with the direction of the blasting pattern rotated by

90 degrees. Complete passes of the specimen were completed so that the total blasting time was 30 minutes. Typically, two or three total passes were finished within 30 minutes of effective blasting time.

Blasting exposed aggregate particles by removing cement paste and chipping away aggregate. After 30 minutes of effective contact abrasion, the specimen was visually checked against the prototype specimen by comparing the size of the exposed surface of the coarse aggregate particles. If the specimen matched the prototype, then the abrasion was complete. If the specimen required more abrasion, the procedures were repeated until the abrasion matched the prototype or until the total blasting time reached a maximum of 45 minutes. Complete passes of the specimen were always completed. The speed of the gun movement was adjusted so as to complete an entire pass within the allotted time. Compressed air was used to clean the specimen of all dust and grit. Cleaning the holes on all surfaces of each specimen helped to minimize dust and grit in the drying room environment. The specimen was returned to the drying room.

2.3.6 Procedure for Precision Sampling by Lathe

Cores from test specimens were precision sampled by grinding using the lathe and carbide tool bits specified in Section 2.2.9. Cores were prepared for sampling by securely wrapping duct tape around the base (lower) half of the core and trimming to allow for cutting (precision sampling) on the top half (with ponded surface) of the specimen, maximizing the taped (protected) surface. The purpose of the tape was to facilitate secure gripping of the specimen by the lathe clamps without localized crushing of the specimen and also to provide external support to the specimen during grinding. A three-prong grip was used to clamp specimens securely, hand tightening each grip at least twice.

The outer 5 mm (0.2 in.) of material was removed from each specimen to a depth of more than 25 mm (1 in.) to remove material that may have had chlorides washed out during the wet drilling process. For this step, the tooling geometry was adjusted to the work piece so that the bit was angled perpendicular to the specimen for cutting from the side.

Once the outer 5 mm (0.2 in.) was removed, the tooling geometry was repositioned to perform precision sampling by cutting the end of the core. A new or newly sharpened bit was used to cut the end of the core (the ponded surface) square. All lathe surfaces were then brushed and wiped to removed concrete dust. A clean 215×355 mm (8½×14 in.) piece of paper with folded ends was laid below the core for sample collection.

Specimens were precision sampled at depths described later in this section. Cuts were made across the end of the core and concrete powder collected on a clean piece of paper. It was common for pieces of concrete to chip away from the core during precision sampling. Pieces larger than the sample depth or which chipped out of a location outside of the current sampling depth range were discarded. After the cutting for a depth range was completed, the sample from the paper was placed in a Ziploc bag that was labeled with the batch number, core number, sample depth, operator's initials, date, and an indication of presence or absence of slag. The presence of slag was noted so that a modified chloride content testing procedure would be used, as described in Section 2.5.

The machine surfaces were cleaned by brushing and wiping between sampling depths to avoid cross-contamination of samples. The operator wore lab gloves when performing precision sampling or when handling samples.

After all samples were cut and collected using the lathe, sample depths were separated according to purpose. Samples from depths of 1 to 3 mm (0.04 to 0.1 in.), 5 to 7 mm (0.2 to 0.3 in.), 10 to 13 mm (0.4 to 0.5 in.), 16 to 20 mm (0.6 to 0.8 in.) and 20 to 25 mm (0.8 to 1.0 in.) were prepared for chloride testing. Samples from depths of 0 to 1 mm (0 to 0.04 in.), 3 to 5 mm (0.1 to 0.2 in.), 7 to 10 mm (0.3 to 0.4 in.) and 13 to 16 mm (0.5 to 0.6 in.) were stored.

Samples to be tested for chlorides were crushed to fine powder using a ceramic mortar and pestle until all material passed a 0.300 mm (No. 50) sieve. A grinding action using pressure to crush sample particles, rather than a pounding action, was used. The mortar and pestle were cleaned between each sample and care was used to not cross-contaminate samples.

The completion of precision sampling and grinding specimens for one core took, on average, approximately three hours.

Testing was attempted on specimens made with quartzite from South Dakota. All attempts at sampling using the precision sampling by lathe procedure described in this section were not successful, because the harder quartzite aggregate caused the carbide tool bits to melt. Development of a new procedure using diamond tipped core bits is recommended for concretes containing quartzite or other hard aggregate.

2.4 PONDING TEST

Testing was performed in accordance with AASHTO T 259-02 (2002), "Standard Method of Test for Resistance of Concrete to Chloride Ion Penetration," with some exceptions (noted in this section). The materials and apparatus are described in Section 2.2, and the methods are described in Section 2.3.

Four specimens were made and tested for some of the experimental programs, one being a control specimen to determine the background chloride content, as noted in Section 2.7. Three specimens were made and tested for the balance of the experimental programs and the background chloride content was assumed. This was reasonable because the materials and procedures remained constant throughout the testing programs.

The specimens were 300 mm (12 in.) square in accordance with the AASHTO T 259-80 (1980) version of the standard method rather than the AASHTO T 259-02 (2002) version. The larger size facilitated the removal of multiple cores from the specimens. The cores were removed with a minimum of 50 mm (2 in.) clear spacing from an edge and 25 mm (1 in.) clear spacing from a dam.

Curing times, materials, and quantities for each of the programs are described in Section 2.7. The length of curing was 7, 14, or 28 days. The length of drying was 28 days after curing and prior to ponding, except for batches 378, 380, and 387, which were dried for 31, 29, and 29 days, respectively.

Abrasion was performed on the ponded surface by sandblasting, as described in Section 2.3.5. For those specimens tested for background chlorides, sampling was performed one day prior to ponding. Specimens were ponded for 90 days, except for batches 358, 380 and 387 which were ponded for 90½, 89, and 89 days, respectively.

After the ponding cycle was completed, 76-mm (3-in.) diameter cores were cut from specimens, as described in Section 2.2.8. Cores were precision sampled with a lathe, as described in Section 2.3.6. Sample depths of 0 to 1 mm (0 to 0.04 in.), 1 to 3 mm (0.04 to 0.1 in.), 3 to 5 mm (0.1 to 0.2 in.), 5 to 7 mm (0.2 to 0.3 in.), 7 to 10 mm (0.3 to 0.4 in.), 10 to 13 mm (0.4 to 0.5 in.), 13 to 16 mm (0.5 to 0.6 in.), 16 to 20 mm (0.6 to 0.8 in.), 20 to 25 mm (0.8 to 1.0 in.) were collected.

The chloride content of the samples was determined in accordance with AASHTO T 260-97, as described in Section 2.5.

2.5 CHLORIDE CONTENT TEST

The chloride content of samples was determined in accordance with AASHTO T 260-97, "Standard Method of Test for Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials." The chloride content was determined using Procedure A - Determination of Water-Soluble Chloride Ion Content by Potentiometric Titration (Laboratory Test Method). Sampling and testing procedures, reagents, and calculations followed the standard, except for the following changes.

Specimen sampling and preparation was preformed as described in Section 2.3.6.

All water used in testing and for cleaning equipment was reverse osmosis filtered, subsequently deionized, and finally tested for chloride content by electrode probe prior to use.

Stirring was completed by hand-swirling covered beakers containing samples every 30 seconds during the five-minute boiling process.

Samples containing ground-granulated blast furnace slag (GGBFS) had 3 mL of 30 percent hydrogen peroxide solution added, as required in AASHTO T 260.

2.6 MIX PROPORTIONING

The Low-Cracking High-Performance Concrete (LC-HPC) mixtures used for this study were designed to reduce cracking in bridge decks. This study compares the permeability of optimized LC-HPC mixtures and non-optimized mixtures commonly used for bridge deck applications. LC-HPC concrete is designed for minimal shrinkage for the purpose of reducing cracking in bridge decks (Lindquist 2008). The goal of concrete mixture optimization is to produce useable concrete with a dense aggregate gradation and low cement paste content while maintaining good workability and meeting project specifications (McLeod 2005).

Optimization emphasizes providing a total aggregate gradation (all size fractions) that includes intermediate-size fractions to fill the voids between large particles. Intermediate-sized particles, particularly particles retained on the 4.75-mm (No. 4), 2.36-mm (No. 8) and 1.16-mm (No. 16) sieves, are required for an optimized aggregate blend, filling the voids between the larger particles and making it possible to reduce the cement paste content while maintaining workability. An optimized aggregate gradation generally has the largest percentage of the material retained on the intermediate sieve sizes, and smaller amounts on the largest and smallest sieve sizes. Aggregate optimization can aid workability and reduce paste content. Reducing paste content will minimize concrete shrinkage and, in turn, cracking in bridge decks.

Shilstone (1990) quantified concrete mix optimization based on the total aggregate gradation and the cement content of the mixture. McLeod (2005) introduced a rational approach towards optimization, introducing an ideal, or optimum, aggregate gradation and a method of blending aggregates to closely match the actual total gradation to the ideal gradation, while accounting for the cement content of the mixture and the maximum size aggregate (MSA). Lindquist (2008), then, further developed these concepts, describing how the ideal (optimum) gradation and concrete mix design changes with changes in the maximum size aggregate (MSA). Lindquist completed KU MIX©, a free computer program, developed at the University of Kansas, that is used to design optimized concrete mixtures.

The LC-HPC concrete used in this study was optimized using KU MIX©. For the design of an optimized mixture, the paste content (by volume), *w/cm* ratio, maximum size aggregate (MSA), and air content are chosen first. These values, along with the properties of the available materials are used by KU MIX© to calculate the final gradations and mix proportions. To determine the effect of mineral admixtures, cement replacement with mineral admixtures, such as silica fume or ground-granulated blast furnace slag (GGBFS), is performed by volume so as to maintain a constant paste volume.

Mix design details are provided for each testing program in Appendix A.

Aggregate optimization is a process of determining the proportions of aggregates so that the total combined gradation is as dense as possible so the paste demand is minimized while providing enhanced workability for the mixture. Aggregate optimization is key for the reduction of paste in the mix design while maintaining the workability and cohesion of the mixture. An optimized combined aggregate gradation contains all aggregate size fractions including the intermediate-sized fractions to fill the void between the large particles.

An *optimized* aggregate gradation is a gradation that closely matches an *ideal* gradation with all aggregate size fractions present. An *ideal* gradation plots as a "haystack" shape on the percent retained chart and plots in the center of the optimum region on the Modified Coarseness Factor Chart (MCFC). The process of optimizing a particular set of aggregates involves choosing aggregate proportions so the combined aggregate gradation matches the idea gradation as closely as possible. One method for optimizing aggregate gradations and proportioning the resulting concrete mix design is the KU Mix method, initially investigated by McLeod (2005) and completed by Lindquist et al. (2008). A Microsoft Excel spreadsheet enhanced with Visual Basic for Applications designed to perform the KU Mix optimization as described in Lindquist et al. (2008) is available for free download at www.iri.ku.edu.

2.7 TESTING PROGRAMS

The laboratory portion of this study includes 33 batches of concrete that are used to compare the effects of paste content, curing period, *w/cm* ratio, cement type, mineral admixture (silica fume and ground granulated blast furnace slag), shrinkage reducing admixture (SRA), and the use of standard DOT mixtures, on the permeability of concrete, as measured by the 90-day ponding test. As discussed previously, this research is part of the ongoing investigation aimed at building LC-HPC bridge decks described in Chapter 1. Laboratory work supporting this study involves producing concrete on an ongoing basis with concrete batches numbered sequentially. The batch numbers reported in this study represent those produced for permeability testing. The 33 batches reported in this study are shown in Table 2.6.

The ongoing investigation aimed at building LC-HPC bridge decks discussed in Chapter 1 has developed two benchmark mixtures for their low-cracking, low-shrinkage, and constructability properties. These benchmark mixtures are often used in this study as controls to compare the effects of the variables in this study with the LC-HPC concrete currently being produced and cast in the field. The two benchmark mixtures contain 317 kg/m^3 (535 lb/yd^3) of portland cement, no mineral admixtures, an optimized aggregate gradation, 1-in. maximum sized aggregate (MSA), granite coarse aggregate, an air content of 8%, and a *w/c* ratio of 0.42 or 0.45. They are cured for 14 days. For this permeability study, these benchmark mixtures are cast using limestone coarse aggregate.

The concrete used in this study was prepared according to the procedures described in this chapter. Optimized aggregate gradations were used unless otherwise noted. Plastic concrete was tested for slump (ASTM C143), air content (ASTM C173), and temperature (ASTM C1064). Batches 234-246 were cast with 75±13 mm (3±½ in.) slump. All other concrete was cast with 7525 mm (3±1 in.) slump, except Batches 131, 133, 139, and 146, which were cast at slumps of 145 mm (5 3/4 in.), 25 mm (1 in.), 30 mm (1 1/4 in.), and 110 mm (4 1/4 in.), respectively. All concrete in this study contained entrained air. Air content, as tested by the volumetric method, was within 1 % of the design values for Batches 131 through 164, and between 7.9% and 8.9% for Batches 234 through 424, with four exceptions. The design air content for Batch 131 was 6%, but it was cast at 8.9%; the design air content for Batch 133 was 8%, but was cast at 6.9%; the design air content for Batch 146 was 8%, but it was cast at 9.15%; and the design and measured air contents for Batch 387 was 6.5% and 5.9% respectively. Concrete temperature was controlled as necessary using liquid nitrogen while mixing, as described in Section 2.3.1. Concrete temperature was maintained between 18.9º and 22.2ºC (66º and 72ºF) for Batches 131 through 164, and between 21.1º and 23.9ºC (70º and 75 ºF) for Batches 234 through 424, with one exception. Batch 161 was cast at 24.4ºC (76ºF). Cement replacement with mineral admixtures was preformed on a volumetric basis to maintain a constant paste content for comparison with mixtures containing 100% portland cement. In these cases, the water was also adjusted to maintain the *w/cm* ratio.

Table 2.6 Permeability Batches

	Batch No.	Batch Description Paste %-Cement Factor[1]-% Cementitious Material[2]-*w/cm*-Admixture-Additional Description	Curing Period, days
1	131	26.9%-602-100% I/II-0.44-KDOT	7
2	133	29.6%-729-100% I/II-0.37-MoDOT modified	7
3	139	24.2%-535-100% I/II-0.45	7
4	141	24.2%-535-100% I/II-0.45	7
5	144	24.2%-535-100% CG II-0.45	7
6	146	24.2%-535-100% I/II-0.45-2% SRA	7
7	148	22.5%-497-100% I/II-0.45	7
8	161	24.2%-535-100% I/II-0.45	14
9	164	24.2%-535-100% CG II-0.45	7, 14, 28
10	234	23.1%-535-100% I/II-0.41	7, 14
11	235	23.7%-535-100% I/II-0.43	7, 14
12	239	24.4%-535-100% I/II-0.45	7, 14
13	240	23.1%-535-100% MG II-0.41	7, 14
14	244	23.7%-535-100% MG II-0.43	7, 14
15	246	24.4%-535-100% MG II-0.45	7, 14
16	328	23.3%-535-60% G100-0.42	14
17	330	23.3%-583-100% I/II-0.36	14
18	334	23.3%-566-100% I/II-0.38	14
19	335	23.3%-550-100% I/II-0.40	14
20	338	23.3%-535-100% I/II-0.42	14
21	347	23.2%-535-60% G120-0.42	14
22	351	21.6%-497-60% G120-0.42	14
23	354	21.6%-497-60% G120 6% SF-0.42	14
24	355	20.5%-460-60% G120 6% SF-0.42	14
25	358	20.5%-460-80% G120 6% SF-0.42	14
26	378	23.3%535-60% G100 6% SF-0.42	14
27	380	23.3%-535-6% SF-0.42	14
28	381	23.3%-535-3% SF-0.42	14
29	385	23.3%-535-100% I/II-0.42-1% SRA	14
30	387	26.9%-602-100% I/II-0.44-KDOT	14
31	388	21.6%-497-100% I/II-0.42	14
32	424	23.3%-535-30% G120-0.42	14
33	520	24.4%-535-100% I/II-0.45-2% SRA	14

[1] Cement Factor indicates the weight of 100% portland cement (specific gravity of 3.20) in lb/yd^3 that has an equivalent volume to the batch cementitious materials.
[2] % Cementitious Material indicates the percent of the total cementitious material by volume. Additional volume not indicated is Type I/II cement. Notation includes: I/II = Type I/II cement, MG II = medium ground Type II cement, CG II = coarse ground Type II cement, G100 = Grade 100 GGBFS, G120 = Grade 120 GGBFS, SF = Silica Fume.

2.7.1 Program 1 – Paste Content

Program 1 examines the effect of paste content on concrete permeability. The test matrix is shown in Table 2.7. Mixture proportions and concrete properties are provided in Appendix 1, Table A.1. Program 1 involves four sets of tests including two different *w/cm* ratios, 0.42 and 0.45, binary mixtures containing slag, and ternary mixtures containing silica fume and slag. As with all control mixtures in this study, the control mixtures for this program are 100% portland cement with *w/cm* ratios of either 0.42 or 0.45, cement content of either 318 kg/m^3 (535 lb/yd^3) or 295 kg/m^3 (497 lb/yd^3), and 8% entrained air content. Set 1 compares the permeability of concrete mixtures with 100% portland cement and a *w/cm* ratio of 0.42 at paste contents of 23.3% and 21.6%. Similarly, Set 2 compares concrete mixtures with 100% portland cement and a *w/cm* ratio of 0.45 at paste contents of 24.2% and 22.5%. Set 3 considers concrete mixtures with 60% of the portland cement replaced with GGBFS, compared at paste contents of 23.3% and 21.6%. Finally, Set 4 investigates ternary mixtures with 60% GGBFS and 6% silica fume, compared at paste contents of 21.6% and 20.5%, and compares the results with the 100% portland cement control mixture.

Table 2.7 Test Program 1 – Paste Content

Set	Set Description	Batch No.	Batch Description	*w/cm*	Paste Content, %
1	0.42 *w/cm* ratio	338	23.3%-535-100% I/II-0.42	0.42	23.3
		388	21.6%-497-100% I/II-0.42		21.6
2	0.45 *w/cm* ratio	139	24.2%-535-100% I/II-0.45	0.45	24.2
		148	22.5%-497-100% I/II-0.45		22.5
3	Slag	347	23.2%-535-60% G120-0.42	0.42	23.2
		351	21.6%-497-60% G120-0.42		21.6
4	Ternary	354	21.6%-497-60% G120 6% SF-0.42	0.42	21.6
		355	20.5%-460-60% G120 6% SF-0.42		20.5

2.7.2 Program 2 – Curing

Program 2 examines the effect of curing time on the permeability of concrete, including 7, 14, and 28-day curing periods. The test matrix is shown in Table 2.8. Mixture proportions and concrete properties are provided in Appendix 1, Table A.2. Program 2 involves eight sets. Set 1 compares 7 and 14-day curing periods for mixtures with Type I/II cement, a 0.45 *w/cm* ratio, and 24.2% paste content. Set 2 compares 7, 14, and 28-day curing periods for mixtures with coarse ground Type II cement, a 0.45 *w/cm* ratio, and 24.2% paste content. Sets 3 and 4 investigate the effect of 7 and 14 days of curing for mixtures with Type I/II (Set 3) and medium ground Type II (Set 4) cement, a *w/c* ratio of 0.41, and 23.1% paste content. Sets 5 and 6 investigate the effect of 7 and 14 days of curing for mixtures with Type I/II (Set 5) and medium ground Type II (Set 6) cement, a *w/c* ratio of 0.43, and 23.7% paste content. Sets 7 and 8 investigate the effect of 7 and 14 days curing for mixtures with Type I/II (Set 7) and medium ground Type II (Set 8) cement, a *w/c* ratio of 0.45, and 24.4% paste content.

Table 2.8 Test Program 2 – Curing

Set	Set Description	Batch No.	Batch Description	Curing Period, days	*w/cm*	Paste Content, %
1	I/II – 0.45 *w/cm*	139 141 161	24.2%-535-100% I/II-0.45 24.2%-535-100% I/II-0.45 24.2%-535-100% I/II-0.45	7 7 14	0.45	24.2
2	CG II – 0.45 *w/c*	144 164-7 164-14 164-28	24.2%-535-100% CG II-0.45 24.2%-535-100% CG II-0.45-7 24.2%-535-100% CG II-0.45-14 24.2%-535-100% CG II-0.45-28	7 7 14 28	0.45	24.2
3	I/II – 0.41 *w/c*	234-7 234-14	23.1%-535-100% I/II-0.41	7 14	0.41	23.1
4	MG II – 0.41 *w/c*	240-7 240-14	23.1%-535-100% MG II-0.41	7 14	0.41	23.1
5	I/II – 0.43 *w/c*	235-7 235-14	23.7%-535-100% I/II-0.43	7 14	0.43	23.7
6	MG II – 0.43 *w/c*	244-7 244-14	23.7%-535-100% MG II-0.43	7 14	0.43	23.7
7	I/II – 0.45 *w/c*	239-7 239-14	24.4%-535-100% I/II-0.45	7 14	0.45	24.4
8	MG II – 0.45 *w/c*	246-7 246-14	24.4%-535-100% MG II-0.45	7 14	0.45	24.4

2.7.3 Program 3 – Water-Cementitious Material Ratio

Program 3 examines the effect of *w/cm* ratio on the permeability of concrete. The test matrix is shown in Table 2.9. Mixture proportions and concrete properties are provided in Appendix 1, Table A.3. Program 3 involves five sets of mixtures with either a single cement content, or a single paste content. Each of the sets compares multiple *w/c* ratios for mixtures with paste contents of 24.4% or less and curing periods of 7 or 14 days. Sets 1 and 2 are used to compare concrete mixtures containing 318 kg/m^3 (535 lb/yd^3) of Type I/II cement and *w/cm* ratios of 0.41, 0.43, and 0.45, with 7 (Set 1) and 14-day (Set 2) curing periods. Sets 3 and 4 compare concrete mixtures containing 318 kg/m^3 (535 lb/yd^3) of medium ground Type II cement and *w/cm* ratios of 0.41, 0.43, and 0.45, and cured for 7 (Set 3) or 14 (Set 4) days. Set 5 is used to compare concrete mixtures with a paste content of 23.3% and *w/cm* ratios of 0.36, 0.38, 0.40, and 0.42 cured for 14-days.

Table 2.9 Test Program 3 – Water-Cementitious Material Ratio

Set	Set Description	Batch No.	Batch Description	*w/cm*	Paste Content, %
1	535-I/II-7	234-7	23.1%-535-100% I/II-0.41	0.41	23.1
		235-7	23.7%-535-100% I/II-0.43	0.43	23.7
		239-7	24.4%-535-100% I/II-0.45	0.45	24.4
2	535-I/II-14	234-14	23.1%-535-100% I/II-0.41	0.41	23.1
		235-14	23.7%-535-100% I/II-0.43	0.43	23.7
		239-14	24.4%-535-100% I/II-0.45	0.45	24.4
3	535-MG II-7	240-7	23.1%-535-100% MG II-0.41	0.41	23.1
		244-7	23.7%-535-100% MG II-0.43	0.43	23.7
		246-7	24.4%-535-100% MG II-0.45	0.45	24.4
4	535-MG II-14	240-14	23.1%-535-100% MG II-0.41	0.41	23.1
		244-14	23.7%-535-100% MG II-0.43	0.43	23.7
		246-14	24.4%-535-100% MG II-0.45	0.45	24.4
5	23.3% Paste	330	23.3%-583-100% I/II-0.36	0.36	23.3
		334	23.3%-566-100% I/II-0.38	0.38	23.3
		335	23.3%-550-100% I/II-0.40	0.40	23.2
		338	23.3%-535-100% I/II-0.42	0.42	23.3

2.7.4 Program 4 – Cement Type

Program 4 examines the effect of cement type on the permeability of concrete. The test matrix is shown in Table 2.10. Mixture proportions and concrete properties are provided in Appendix 1, Table A.4. Program 4 involves eight sets comparing types of cement at *w/c* ratios of 0.41, 0.43, and 0.45.

Set 1 compares concrete mixtures with 318 kg/m^3 (535 lb/yd^3) of either Type I/II or Type II coarse ground cement and a *w/cm* ratio of 0.45, for 7 and 14-day curing periods. Set 2 compares concrete mixtures with 318 kg/m^3 (535 lb/yd^3) of Type II coarse ground cement and a *w/cm* ratio of 0.45 cured for 7 and 14-days. Sets 3 and 4 compare concrete mixtures with *w/cm* ratios of 0.45 and 318 kg/m^3 (535 lb/yd^3) of Type I/II and Type II medium ground cement, cured for 7 (Set 3) and 14 (Set 4) days. Similarly, Sets 5 and 6 compare concrete mixtures with *w/cm* ratios of 0.43 and 318 kg/m^3 (535 lb/yd^3) of Type I/II and Type II medium ground cement, cured for 7 (Set 5) and 14 (Set 6) days. Sets 7 and 8 compare concrete mixtures with *w/cm* ratios of 0.41 and 318 kg/m^3 (535 lb/yd^3) of Type I/II and Type II medium ground cement, cured for 7 (Set 7) and 14 (Set 8) days.

Table 2.10 Test Program 4 – Cement Type

Set	Set Description	Batch No.	Batch Description	*w/cm*	Paste Content, %
1	CG II 0.45 7-day	139 141 144 164	24.2%-535-100% I/II-0.45-7 24.2%-535-100% I/II-0.45-7 24.2%-535-100% CG II-0.45-7 24.2%-535-100% CG II-0.45-7	0.45	24.2
2	CG II 0.45 14-day	161 164-14	24.2%-535-100% I/II-0.45-14 24.2%-535-100% CG II-0.45-14	0.45	24.2
3	MG II 0.45 7-day	239-7 246-7	24.4%-535-100% I/II-0.45-7 24.4%-535-100% MG II-0.45-7	0.45	24.4
4	MG II 0.45 14-day	239-14 246-14	24.4%-535-100% I/II-0.45-14 24.4%-535-100% MG II-0.45-14	0.45	24.4
5	MG II 0.43 7-day	235-7 244-7	23.7%-535-100% I/II-0.43-7 23.7%-535-100% MG II-0.43-7	0.43	23.7
6	MG II 0.43 14-day	235-14 244-14	23.7%-535-100% I/II-0.43-14 23.7%-535-100% MG II-0.43-14	0.43	23.7
7	MG II 0.41 7-day	234-7 240-7	23.1%-535-100% I/II-0.41-7 23.1%-535-100% MG II-0.41-7	0.41	23.1
8	MG II 0.41 14-day	234-14 240-14	23.1%-535-100% I/II-0.41-14 23.1%-535-100% MG II-0.41-14	0.41	23.1

2.7.5 Program 5 – Mineral Admixtures

Program 5 examines the effect of mineral admixtures on the permeability of concrete. The test matrix is shown in Table 2.11. Mixture proportions and concrete properties are provided in Appendix 1, Table A.5. Program 5 involves six sets with two sets include ground granulated blast furnace slag (GGBFS), one set involves silica fume, and three sets involve ternary mixtures containing both GGBFS and silica fume. The replacement of cement with mineral admixtures is preformed on a volumetric basis to maintain a constant volume of paste (water and cementitious material); the mixtures have a *w/cm* ratio of 0.42.

The two GGBFS sets are used to study the effect of the grade of GGBFS and the percent replacement of portland cement with GGBFS. Set 1 compares concrete mixtures in which 60% of the portland cement is replaced with Grades 100 or 120 GGBFS. Set 2 compares concrete mixtures which 30% or 60% of the portland cement has been replaced with Grade 120 GGBFS.

The silica fume series (Set 3) is used to study the effect of percentage replacement of cement at 0%, 3% or 6% silica fume.

The three ternary mixture sets (4, 5, and 6) involve either Grade 100 or Grade 120 GGBFS and silica fume at various paste contents. Set 4 is used to compare a 100% portland cement mixture, with 23.2% paste, with a binary mixture containing 60% Grade 100 GGBFS, and a ternary mixture containing 60% Grade 100 GGBFS and 6% silica fume. Similarly, Set 5 is used to compare a 100% portland cement mixture, with 21.6% paste, with a binary mixture containing 60% Grade 120 GGBFS and a ternary mixture containing 60% GGBFS and 6% silica fume.

Set 6 includes binary and ternary mixtures with decreasing paste contents to determine whether the decrease in permeability due to the mineral admixtures is enough to make up for the loss in permeability due to reduced paste content. Set 6 compares benchmark control mixtures, containing 100% portland cement and paste contents of 23.3% or 21.6%, with a binary mixture containing 60% G120 GGBFS and paste content of 21.6%, a ternary mixture containing 60% G120 GGBFS and 6% SF at a paste content of 20.5%, and a ternary mixture containing 80% Grade 120 GGBFS and 6% SF at a paste content of 20.5%.

Table 2.11 Test Program 5 – Mineral Admixtures

Set	Set Description	Batch No.	Batch Description	*w/cm*	Paste Content, %
1	GGBFS Grade	338 328 347	23.3%-535-100% I/II-0.42 23.3%-535-60% G100-0.42 23.2%-535-60% G120-0.42	0.42	23.3
2	G120	338 424 347	23.3%-535-100% I/II-0.42 535 – 30% G120 23.2%-535-60% G120-0.42	0.42	23.3
3	Silica Fume	338 381 380	23.3%-535-100% I/II-0.42 23.3%-535-3% SF-0.42 23.3%-535-6% SF-0.42	0.42	23.3
4	G100 and Silica Fume	338 328 378	23.3%-535-100% I/II-0.42 23.3%-535-60% G100-0.42 23.3%535-60% G100 6% SF-0.42	0.42	23.3
5	G120 and Silica Fume	388 351 354	21.6%-497-100% I/II-0.42 21.6%-497-60% G120-0.42 21.6%-497-60% G120 6% SF-0.42	0.42	21.6
6	Reduced Paste	338 388 351 355 358	23.3%-535-100% I/II-0.42 21.6%-497-100% I/II-0.42 21.6%-497-60% G120-0.42 20.5%-460-60% G120 6% SF-0.42 20.5%-460-80% G120 6% SF-0.42	0.42 0.42 0.42 0.42 0.42	23.3 21.6 21.6 20.5 20.5

2.7.6 Program 6 – Shrinkage Reducing Admixture (SRA)

Program 6 examines the effect of a Shrinkage Reducing Admixture (SRA) on the permeability of concrete. The test matrix is shown in Table 2.12. Mixture proportions and concrete properties are provided in Appendix 1, Table A.6. Program 6 involves two sets, including the use of 2% SRA by weight of cement at a *w/cm* ratio of 0.45 and 1% SRA by weight of cement at a *w/cm* ratio of 0.42. Set 1 consists of concrete mixtures with a paste content of 24.2%, a *w/cm* ratio of 0.45 and cured for 7 and 14 days. A mixture containing no SRA is compared with a mixture containing 2% SRA. Set 2 consists of concrete mixtures with a paste content of 23.3% and a *w/cm* ratio of 0.42 cured for 14 days. A mixture containing no SRA is compared with a mixture containing 1% SRA.

Table 2.12 Test Program 6 – Shrinkage Reducing Admixture (SRA)

Set	Set Description	Batch No.	Batch Description	*w/cm*	Paste Content, %
1	2% SRA 0.45 *w/cm*	139	24.2%-535-100% I/II-0.45	0.45	24.2
		146	24.2%-535-100% I/II-0.45-2% SRA		
2	1% SRA 0.42 *w/cm*	338	23.3%-535-100% I/II-0.42	0.42	23.3
		385	23.3%-535-100% I/II-0.42-1% SRA		

2.7.7 Program 7 – DOT Standard Mixtures

Program 7 examines the permeability of two concretes developed for low-cracking properties with three standard DOT mixtures. The test matrix is shown in Table 2.13. Mixture proportions and concrete properties are provided in Appendix 1, Table A.7. Two sets of tests are used to compare benchmark LC-HPC mixtures with standard DOT mixtures used on bridge decks. Set 1 compares a benchmark LC-HPC mixture containing 24.2% paste, at a *w/c* ratio of 0.45 and design air content of 8.0%, with a mixture containing 26.9% paste, a *w/c* ratio of 0.44, and a design air content of 6.0%, and a mixture containing 29.6% paste, a *w/c* ratio of 0.37, and a design air content of 5.0%. Set 1 was cured for 7 days. Set 2 compares a benchmark LC-HPC mixture containing 23.3% paste, at a *w/c* ratio of 0.42 and design air content of 8.0%, with a mixture containing 26.9% paste, a *w/c* ratio of 0.44, and a design air content of 6.5%. Set 2 was cured for 14 days.

Table 2.13 Test Program 7 – DOT Standard Mixtures

Sets	Set Description	Batch No.	Batch Description	*w/cm*	Paste Content, %
1	7-day cure	139	24.2%-535-100% I/II-0.45	0.45	24.2
		131	26.9%-602-100% I/II-0.44-KDOT	0.44	26.9
		133	29.6%-729-100% I/II-0.37-MoDOT modified	0.37	29.6
2	14-day cure	338	23.3%-535-100% I/II-0.42	0.42	23.3
		387	26.9%-602-100% I/II-0.44-KDOT	0.44	26.9

2.8 CRACK SURVEY TECHNIQUES AND CRACK DENSITY DETERMINATION

On-site crack surveys were performed for each of the LC-HPC and control bridges included in this study. Surveys were scheduled to be performed at 1 and 2 years after construction. Actual deck ages at the time of survey, however, varied somewhat due to the weather requirements for the survey techniques. Previous bridge deck cracking studies at the University of Kansas describe the crack survey techniques and methods of crack density determination in detail (Lindquist et al. 2005, Miller and Darwin 2000, Schmitt and Darwin 1995). Techniques described in these references quantify the amount of cracking on a bridge deck and have been shown to provide reproducible results. A scaled crack map and the average crack density (meters of crack length per square meter of deck) for the bridge deck are produced. The crack density is used to evaluate the amount of cracking on a bridge deck and compare the performance of different decks.

Chapter 3

LABORATORY RESULTS - CHLORIDE PENETRATION IN CONCRETE TEST SPECIMENS

3.1 GENERAL

This chapter presents the analysis and results for the seven test programs described in Section 2.7 aimed at measuring the relative resistance of concrete mixtures to chloride diffusion. The tests measured chloride diffusion in long-term salt-ponding specimens and the results include chloride profiles, effective diffusion coefficients, surface concentrations and the depth of chloride penetration at twice the corrosion threshold. Chloride profiles were measured in the top 25 mm (1 in.) of concrete exposed to chlorides to compare the effects of various parameters on chloride ingress.

Chloride contents were measured and diffusion properties calculated using the procedures described in Chapter 2. Thirty three batches of concrete were cast, some with multiple curing times, for a total of 41 different AASHTO T 259 salt ponding (Section 2.4) permeability tests. Three specimens were cast for each of the tests. Precision depth sampling techniques (Section 2.3.6) were used to collect samples from nine depth ranges. Five of the nine samples for each specimen were then tested for chloride concentration (Section 2.5), establishing a chloride profile for the specimen.

Using a least squares regression analysis, Fick's Law was used to model the chloride ingress for each of the three chloride profiles. For each test (three specimens), a single effective diffusion coefficient and three independent surface concentrations were determined.

The depth of penetration for a chloride concentration equal to twice the critical corrosion threshold y_{2CT} was also calculated as a direct measure of chloride ingress into the concrete.

The chloride profiles, the average depth of penetration of twice the corrosion threshold $\overline{y}_{2CT}$, and the effective diffusion coefficient are used to compare the resistance of different concretes to chloride ingress.

3.2 CHLORIDE PROFILES

AASHTO T 259 salt-ponding tests were preformed on three specimens, as described in Sections 2.3 and 2.4, for each of the 41 permeability tests in this study. Samples were collected from cores at depths as described in Section 2.3.6 and tested for chloride concentration according to ASTM T 260, as described in Section 2.5. For each completed salt-ponding test, the chloride concentration was plotted against the sample depth, resulting in a measured profile of chloride concentrations throughout the depth of the specimen. The measured chloride concentrations are presented in Appendix B. For some specimens, several tests were performed on concrete from a given depth. Repeated testing is noted in the raw data and shown on the chloride profiles. Repeated tests from the same specimen and depth were averaged for use in the regression analysis. Anomalous results were apparent and not used in the analysis. All data is reported and those data not used in the analysis are indicated.

3.3 DEPTH OF CHLORIDE PENETRATION

The measured chloride profiles obtained with AASHTO T 259 testing are typically used to model diffusion of chlorides into concrete as discussed later in Section 3.5. In addition to the standard methods, a direct measure of chloride penetration into concrete was desired as another way to compare the ability of different concretes to resist chloride penetration. The direct measure chosen was the depth of penetration of chloride at a concentration equal to twice the critical corrosion threshold.

McGrath and Hooton (1999) used a similar measure of chloride penetration depth at a chloride concentration equal to 0.1% by mass of concrete, a concentration somewhat higher than twice the critical corrosion threshold. This point was arbitrarily chosen on the chloride profile as an approximation of the boundary between the nearly linear portion of profile (shallow depths) and the curved portion of the profile (greater depths). They reported that the point corresponding to the 0.1% concentration typically provided a precise and reproducible depth measurement. They also noted that lower concentrations (greater depths) were more variable due to the asymptotic shape of the chloride profile curve. For this study, values of 0.1% chloride concentration range from 2.22 to 2.29 kg/m^3 (3.74 to 3.86 lb/yd^3), due to variations in the unit weights for the concrete mixtures. A single value (not a range) of chloride concentration was desired to compare concrete mixtures in this study.

According to Darwin et al. (2007), the average critical chloride corrosion threshold for conventional reinforcing steel on a water-soluble basis is 0.97 kg/m^3 (1.63 lb/yd^3). A chloride concentration equal to twice the critical corrosion threshold, 1.93 kg/m^3 (3.25 lb/yd^3), was chosen for the depth of penetration comparison. This value is slightly lower than the concentration used by McGrath and Hooton (1999).

The depth of chloride penetration with a concentration equal to twice the critical corrosion is denoted y_{2CT}. The y_{2CT} values for each test in this study were determined directly from the raw data for each specimen by linear interpolation. The y_{2CT} values were then averaged for the three specimens in the test to determine the average y_{2CT}, or $\overline{y}_{2CT}$, for the test. Values of y_{2CT} for each specimen are provided in the data tables and shown on the chloride profiles in Appendix B. The $\overline{y}_{2CT}$ results are presented in Table 3.1.

Table 3.1 Depth of chloride content equal to twice the critical corrosion threshold $\bar{y}_{2CT}$

Batch No.	$\bar{y}_{2CT}$ mm (in.)	Batch No.	$\bar{y}_{2CT}$ mm (in.)	Batch No.	$\bar{y}_{2CT}$ mm (in.)
131	14.4 (0.567)	239-7	13.9 (0.548)	354	8.7 (0.340)
133	13.0 (0.511)	239-14	12.6 (0.495)	355	7.0 (0.275)
139	13.0 (0.510)	240-7	13.5 (0.531)	358	7.5 (0.296)
141	13.1 (0.514)	240-14	11.4 (0.449)	378	6.2 (0.244)
144	14.4 (0.565)	244-7	13.1 (0.516)	380	11.5 (0.451)
146	12.3 (0.486)	244-14	14.7 (0.577)	381	11.9 (0.467)
148	12.8 (0.502)	246-7	17.1 (0.673)	385	10.8 (0.424)
161	13.1 (0.515)	246-14	13.6 (0.536)	387	13.1 (0.516)
164-7	13.8 (0.543)	328	9.1 (0.358)	388	14.8 (0.581)
164-14	12.6 (0.495)	330	10.0 (0.392)	424	10.1 (0.399)
164-28	12.0 (0.473)	334	10.2 (0.400)	520	12.0 (0.471)
234-7	13.8 (0.545)	335	12.2 (0.480)		
234-14	12.4 (0.498)	338	11.1 (0.435)		
235-7	11.5 (0.454)	347	10.6 (0.418)		
235-14	11.9 (0.469)	351	10.5 (0.413)		

3.4 BACKGROUND CHLORIDE CONCENTRATIONS

Chlorides can be introduced into concrete from a variety of sources prior to exposure to deicing chemicals. The source of these chlorides may include those naturally present in or due to contamination of the aggregates, cement, water, or admixtures. It is, therefore, necessary to establish the baseline values (background chloride concentrations) in the concrete prior to permeability testing. The background chloride concentrations are used in modeling chloride diffusion with Fick's Law, as described in Section 3.5.

For the 33 batches in this study, background chloride concentrations were determined by one of three methods. For 13 batches, the background levels were measured directly, as described in Section 3.4.1. For the remaining 20 batches, the chloride profiles were analyzed, and based on the profiles, background levels were determined by the "0.08 rule" (five batches) or assumed to be equal to the average of the 13 measured background levels (15 batches), as described in Section 3.4.2.

3.4.1 Measured Background Chloride Concentrations

Thirteen batches were directly measured for background chloride levels with samples obtained from the permeability specimens prior to ponding and according to the method described next. Samples to determine the background chloride concentration in the permeability specimens were obtained after sandblasting and prior to salt ponding using a 6.4 mm (0.25 in.) diameter bit mounted on a drill press. Samples were removed below the "X" mark made on the specimen during the sandblasting procedure (see Section 2.3.5). This location was selected because it was as far as possible from the location of the concrete core removed after ponding. Thus, the location of the background sampling did not intersect the future core, nor did it affect the diffusion of chlorides in the core region during testing. The drill bit was thoroughly cleaned using deionized water prior to sampling. The drilling was perpendicular to the side surface of the specimen. The first 12.7 mm (0.5 in.) of material was discarded, the surface layer of powdered concrete was removed with a vacuum, and the surface of the concrete, the hole, and the drill bit were thoroughly cleaned using a brush and deionized water for the bit. Drilling then continued to a depth of 89 mm (3.5 in.). The powdered concrete sample was collected on a piece of new printer paper. After drilling, samples were transferred to a labeled, plastic zip-lock bag. Three holes were drilled for each of the three specimens in a batch (A, B, and C), and the samples combined to represent the aggregate background chloride concentration of the batch. Background samples were tested for chloride concentration according to AASHTO T 260 (Section 2.5), the same testing method as for the ponded specimens. Test results are shown in Table 3.2 for the 13 batches directly measured for background chloride concentration. The average background chloride concentration was 0.01% by weight of concrete, with a standard deviation of 0.004%.

Table 3.2 Measured background chloride concentrations

Batch No.	Batch Weight	Measured Background [Cl-]	
	kg/m^3 (lb/yd^3)	%	kg/m^3 (lb/yd^3)
234	2240 (3776)	0.00827	0.185 (0.312)
235	2231 (3760)	0.00910	0.203 (0.342)
239	2220 (3742)	0.00993	0.220 (0.371)
240	2240 (3776)	0.00662	0.148 (0.250)
244	2233 (3764)	0.00827	0.185 (0.311)
246	2220 (3742)	0.00827	0.184 (0.310)
328	2222 (3745)	0.0132	0.294 (0.496)
330	2253 (3798)	0.00778	0.175 (0.295)
334	2246 (3786)	0.00745	0.167 (0.282)
335	2241 (3777)	0.00662	0.148 (0.250)
338	2235 (3767)	0.00993	0.222 (0.374)
347	2226 (3752)	0.0199	0.442 (0.745)
520	2215 (3734)	0.00503	0.111 (0.188)

3.4.2 Establishing Background Chloride Concentrations for Batches Not Directly Sampled Prior to Ponding

Some of the concrete batches in this study were not tested for background chlorides. For the 20 batches not tested for background chloride levels, background levels were assumed based on the examination of chloride data using two separate methods, either the 0.08 rule or based on the average of the measured background levels obtained for the batches shown in Table 3.2.

First, the chloride data for each the 20 batches were examined to determine whether the concentrations at the two deepest sample depths differed by more than 0.05 kg/m^3 (0.08 lb/yd^3). If they did not, then the chloride concentration was considered to be at background levels and the background chloride concentration was assumed to be equal to the concentration at the lowest (deepest) depth. This was the case for 5 batches (Batches 354, 355, 358, 378 and 424). If the difference of the average of the two deepest samples was greater than 0.05 kg/m^3 (0.08 lb/yd^3), then the chloride concentration was considered to be decreasing with decreasing depth and with values above the background level.

For the 15 batches that were not directly tested for background chloride concentration and did not meet the 0.08 rule, the background chloride concentration was assumed to be equal to 0.01%, the average result of the 13 batches tested for background chlorides. The one exception was Batch 351, which was assumed to be 0.02%. Batch 351 was cast from the same cement, GGBFS, limestone, fine aggregate and pea gravel samples as Batches 347, 354, 355, 358 and 378. These five batches were tested for background chlorides and had higher than average background chloride concentrations, ranging from 0.0164–0.0285%, indicating that the materials used for these batches had increased chloride contents. It was therefore assumed that Batch 351 also had a higher than average background chloride content. This was also supported by examination of the chloride profile for Batch 351 (Fig. B.30 and Table B.1). The assumed background chloride concentration of 0.02% appears to more accurately reflect the true background chloride content. Batch 351 did not meet the stringent requirements of the 0.08 rule apparently because it had higher permeability than the five batches that did meet the 0.08 rule (Batches 354, 355, 358, 378, and 424).

The assumed background chloride concentrations for the 20 batches not directly measured for background chlorides are presented in Table 3.3.

3.5 MODELING CHLORIDE DIFFUSION USING FICK'S EQUATION

3.5.1 Effective Diffusion Coefficients for a Batch of Concrete

The ingress of chlorides into solid concrete was modeled using Fick's Second Law of Diffusion, Eq. (1.1). This commonly used model provides a useful method for comparing the relative resistance of concretes to chloride penetration. In this model, the measured chloride concentrations from the permeability tests (three specimens per test) and Fick's Second Law are used to calculate an effective diffusion coefficient for the concrete in each test and an apparent surface concentration for each specimen. In their study on the effects of cracking on bridge deck chloride contents, Lindquist et al. (2006) determined apparent surface concentrations for each (bridge deck) sample instead of one apparent surface concentration for the entire deck. The data used for the analysis in this study and the corresponding chloride profile plots (the individual Fick's profiles) are provided in Appendix B.

Table 3.3 Assumed background chloride concentrations for batches not measured for background chlorides

Batch No.	Batch Weight	Assumed Background [Cl-]	
	kg/m^3 (lb/yd^3)	%	kg/m^3 (lb/yd^3)
131	2260 (3810)	0.01	0.226 (0.381)
133	2292 (3863)	0.01	0.229 (0.386)
139	2222 (3745)	0.01	0.222 (0.375)
141	2222 (3745)	0.01	0.222 (0.375)
144	2222 (3745)	0.01	0.222 (0.375)
146	2222 (3745)	0.01	0.222 (0.375)
148	2234 (3765)	0.01	0.223 (0.377)
161	2222 (3745)	0.01	0.222 (0.375)
164	2223 (3747)	0.01	0.222 (0.375)
351	2238 (3772)	0.02	0.448 (0.754)
354	2230 (3764)	0.0281*	0.628 (1.06)
355	2241 (3777)	0.0210*	0.470 (0.792)
358	2238 (3773)	0.0285*	0.639 (1.08)
378	2218 (3738)	0.0164*	0.364 (0.613)
380	2230 (3759)	0.01	0.223 (0.376)
381	2232 (3762)	0.01	0.223 (0.376)
385	2230 (3759)	0.01	0.223 (0.376)
387	2241 (3778)	0.01	0.224 (0.378)
388	2244 (3783)	0.01	0.224 (0.378)
424	2229 (3757)	0.0137*	0.305 (0.515)

* 0.08 Rule

Crank's solution to Fick's Second Law (Lindquist et al. 2006), Eq. (1.3), was used to calculate the effective diffusion coefficient and apparent surface concentrations.

$$C(x,t) = C_i + (C_o - C_i)\left[1 - erf\left(\frac{x}{2\sqrt{D_{eff} \times t}}\right)\right] \tag{1.3}$$

The solution has four degrees of freedom, depth x, time t, apparent surface concentration C_o, and the effective diffusion coefficient D_{eff}. The sample depth x (the average of the sample depth range) and the time of ponding t are known for each specimen from testing. The background (or initial) chloride concentration C_i for each batch is also known (Section 3.4) leaving the apparent surface concentration C_o and the effective diffusion coefficient D_{eff} as unknowns in Eq. (1.3). They were estimated using an iterative least-squares curve fitting technique, fitting Fick's model to the measured chloride data. The calculations begin by assuming initial values for the effective diffusion coefficient and the three surface concentrations (for each of the three specimens). The concentration at each sample depth within the specimen $C(x,t)$ was calculated using Eq. (1.3) for the initially assumed values for D_{eff} and C_o. The values of $C(x,t)$ were numerically integrated over the depth range of each sample and divided by the total sample depth to obtain an average chloride concentration. This was completed for each of the 15 samples (five depths for each of the three specimens) for the test. D_{eff} and the three values of C_o were calculated using the Microsoft Excel 2000 Solver tool to modify the effective diffusion coefficient and the three apparent surface concentrations to minimize the sum of the squared differences between the respective measured chloride concentrations and the average sample

Table 3.4 Effective Diffusion Coefficients D_{eff}

Batch No.	D_{eff} (mm^2/day)	Batch No.	D_{eff} (mm^2/day)	Batch No.	D_{eff} (mm^2/day)
131	0.96	239-7	0.63	354	0.15
133	0.71	239-14	0.52	355	0.14
139	0.84	240-7	0.88	358	0.18
141	0.84	240-14	0.56	378	0.22
144	1.35	244-7	0.82	380	0.37
146	0.73	244-14	1.02	381	0.48
148	0.96	246-7	1.21	385	0.48
161	0.93	246-14	1.02	387	0.62
164-7	1.26	328	0.19	388	0.65
164-14	1.02	330	0.32	424	0.34
164-28	0.91	334	0.31	520	0.89
234-7	0.72	335	0.47		
234-14	0.59	338	0.38		
235-7	0.56	347	0.26		
235-14	0.52	351	0.28		

chloride concentrations predicted by the model. This method was repeated for each group of these permeability test specimens, and the resultant effective diffusion coefficients were used to compare concrete performance. The calculated diffusion coefficients using the three independent surface concentrations are tabulated in Table 3.4. An alternative method to calculate diffusion coefficients is described next in Section 3.5.2.

3.5.2 Effective Diffusion Coefficients for Individual Specimens

An alternative method to estimate the effective diffusion coefficient was accomplished, doing so by determining the individual diffusion coefficients for each specimen. The individual coefficients for the three specimens in each batch were they averaged. The averaged results are nearly identical to the results presented in Table 3.4, but the alternative method has the advantage that individual specimen results provide information regarding the variation in measured concrete performance using the permeability test.

Individual diffusion coefficients were estimated separately for each of the three specimens (A, B and C) using the same method described in Section 3.5.1, except that they were modeled using only chloride concentrations at the five sample depths for each specimen, producing individual surface chloride concentrations and individual effective diffusion coefficients $D_{eff,A}$, $D_{eff,B}$ and $D_{eff,C}$. The effective diffusion coefficient for the test was estimated by averaging the individual effective diffusion coefficients.

In this study, the average of the individual specimen effective diffusion coefficients correlate well with the total effective diffusion coefficient for the test calculated for the batch containing those specimens. The correlation coefficient R^2 for the two methods is 0.9989, with a slope of 1.01, as shown in Fig. 3.1. For all tests, the deviation of the two methods ranges from 0 to 0.037 mm^2/day.

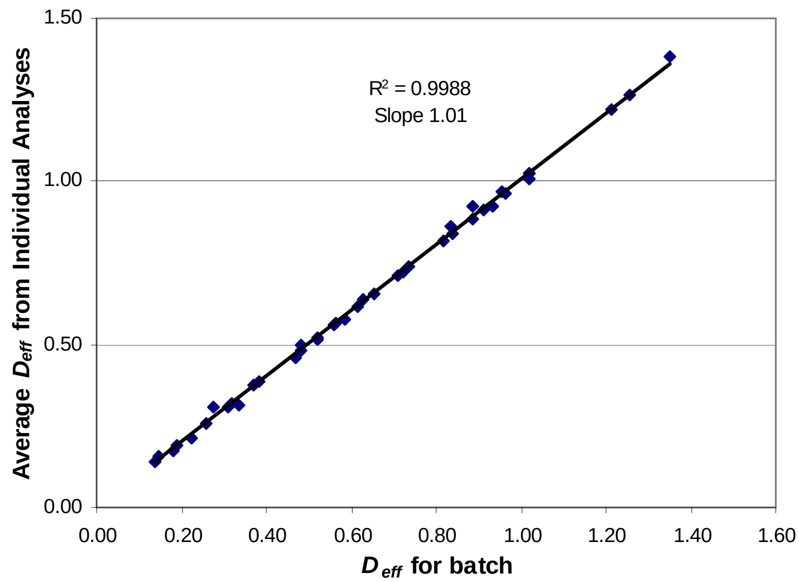


Fig 3.1 D_{eff} for batch versus average D_{eff} from the individual specimen analyses

The individual effective diffusion coefficients provide information about the variation within the permeability tests. In the descriptions of the test results that follow, Sections 3.9 through 3.15, histogram plots compare the effective diffusion coefficients for different concretes. These plots include range bars to indicate the variation in the individual effective diffusion coefficients, providing a sense of the scatter in the results.

3.5.3 Fick's Profiles for a Batch of Concrete

The Fick's profiles provided in the balance of Chapter 3 are produced using the same methodology described in Section 3.5.1, except that one apparent surface concentration is assumed for a batch instead of individual surface concentrations for each of the three test specimens in the batch. As a result, one Fick's profile is produced for each batch instead of three profiles for each of three specimens, representing an average performance of the concrete within a batch.

3.6 STATISTICAL ANALYSIS

Because the sample sizes in this study are relatively small and the differences between the means of these samples is also often small, the Student's t-test is used to help determine whether the means of two normally distributed populations are equal. The Student's t-test can be used for hypothesis testing for two data sets, each characterized by a sample size, mean, and standard deviation. To apply the Student's t-test, certain assumptions must be made about the two populations being tested. The samples are assumed to be normally distributed, the populations have equal variances, and the samples are independent (not paired).

In using the Student's t-test for two-sided hypothesis testing, the null hypothesis is that the unknown true population means μ_1 and μ_2, represented by measured sample means X_1 and X_2, are equal. This null hypothesis is tested at a chosen "level of significance" α, to determine whether to reject the null hypothesis. Rejecting the null hypothesis indicates, in essence, that the means are different. When this occurs the difference in the sample means is said to be "statistically significant." Commonly, $\alpha = 0.05$ is used, indicating a 5 percent chance that the test would incorrectly identify the two population means as different, when in fact they are the same. Equivalently, an $\alpha = 0.05$ indicates that there is a 95% chance of correctly identifying a difference when such a difference exists. Smaller values of α indicate higher levels of statistical significance and make it harder to reject the null hypothesis, that is, it is harder to say that the difference between two means X_1 and X_2 is statistically significant. For this study, the level of significance α is determined for which the t-test rejects the null hypothesis (indicating the population means are different). The levels of significance are provided in the results (Sections 3.9–3.15) for all α of 0.20 (80%) and smaller.

The results of the Student's t-tests are presented in the tables in the results (Sections 3.9–3.15) using the notation "Y α (CI)." The "Y" indicates that, yes there is a statistical difference between the two samples at a statistical significance level of α

and a confidence interval CI of $100 \times (1 - \alpha)$. An "N" indicates that there is no statistical difference, even at a level of significance $\alpha = 0.20$ (80%).

3.7 ADDITIONAL DETAILS

3.7.1 Drying

Results from the ponding tests may be influenced by the drying time that the specimens experience after curing and before sampling. Ideally, the time between deponding and lathe sampling should be minimized, with coring and sampling occurring immediately after deponding. If immediate sampling is not possible, it has been recommended that the cores be sealed in plastic and frozen until sampling is preformed (McGrath and Hooton 1999). In the current study, the time between deponding and lathe sampling varied with the date of testing. Drying times for the batches are shown in Fig. 3.2. The batch descriptions for each of the batch numbers in Fig. 3.2 are provided in Table 2.6. There are three distinct groupings of cast dates, identified as Groups 1, 2 and 3. Group 1 was cast between 6/21/2004 and 7/21/2004, Group 2 was cast between 6/27/2005 and 7/26/2005, and Group 3 was cast between 5/26/2006 and 1/23/2007, with one additional batch cast on 3/18/08. Only one batch (Batch 520) was sealed and frozen during the time between deponding and sampling. The average times between deponding and lathe sampling for Groups 1, 2, and 3 are 72, 211, and 71 days, respectively. Due to the variation in both the drying time and the cementitious material chemistry over time, comparisons of tests between groups are not performed. Dates of the batching and testing are provided in Appendix B.

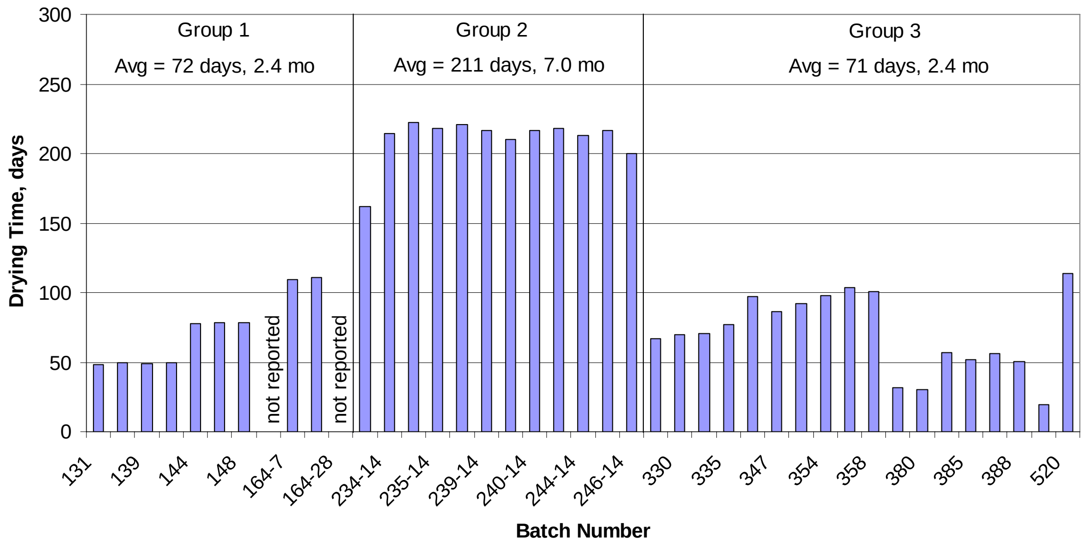


Fig. 3.2 AASHTO T 259 90-day ponding test drying times from deponding to sampling for individual batches

3.7.2 D_{eff} and $\overline{y}_{2CT}$ Results

Multiple methods of evaluating test results can be useful when evaluating concrete permeability tests. The effective diffusion coefficient, obtained through modeling, provides a general measure of the resistance of concrete to chloride penetration. The average depth of chloride penetration at twice the corrosion threshold $\overline{y}_{2CT}$ is a direct measure of chloride ingress into concrete, providing a simple and direct comparison of chloride concentration at a given depth. A chart of D_{eff} and $\overline{y}_{2CT}$ results for all batches in this study is shown in Fig. 3.3, which shows that the two measures of permeability correlate reasonably well. Batch descriptions for each of the batch numbers in Fig. 3.3 are provided in Table 2.6. The degree of correlation between the model results and the direct measure of chloride permeability is illustrated further by the plot of D_{eff} versus $\overline{y}_{2CT}$ in Fig. 3.4, which has an R^2 value of 0.69, showing reasonable correspondence of the two parameters. If the five batches with the lowest value of D_{eff}, corresponding to the batches containing G100 GGBFS and the ternary mixtures, are removed from the analysis, R^2 drops to 0.61.

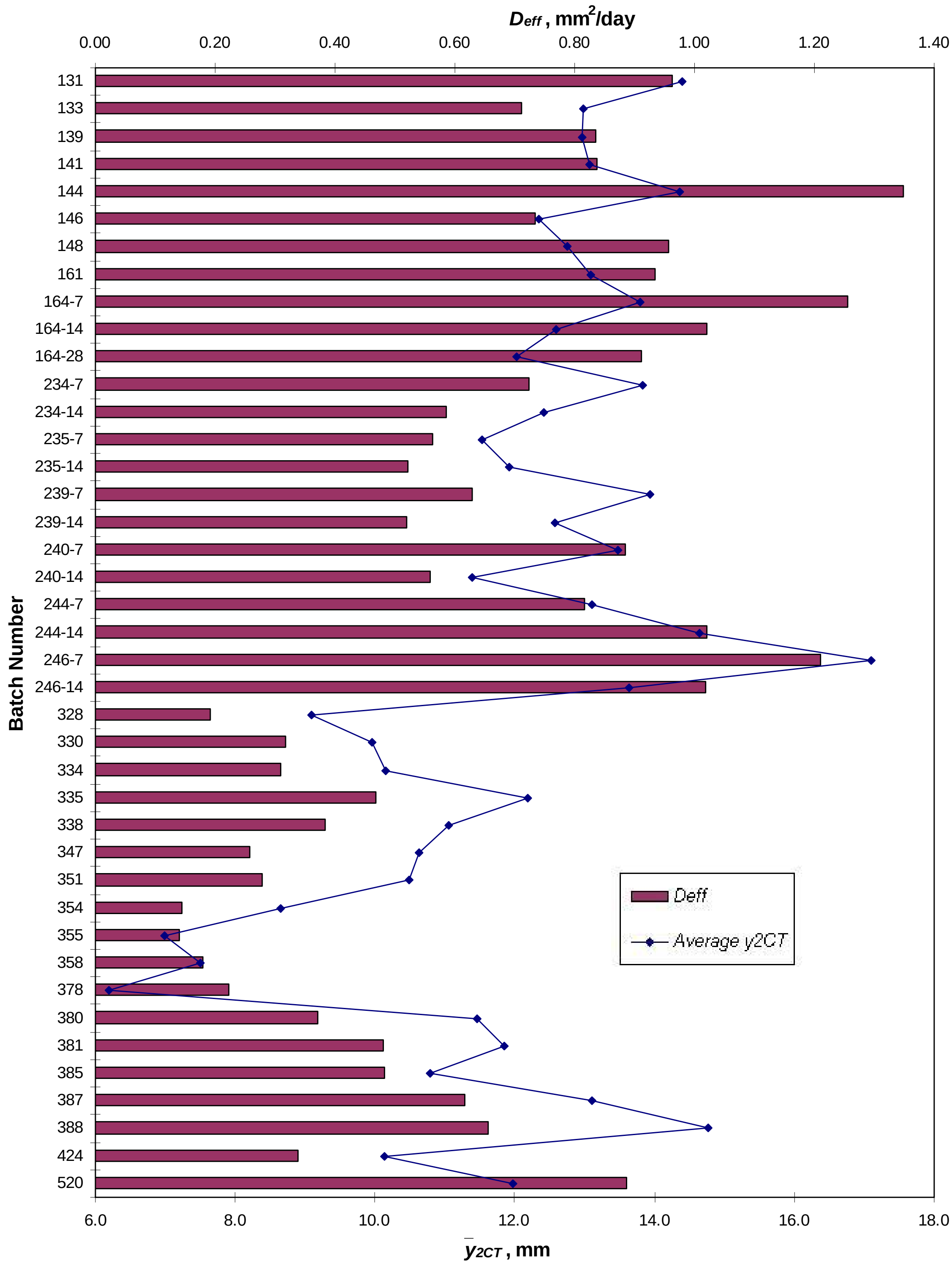


Fig 3.3 Bar graph showing D_{eff} and $\overline{y}_{2CT}$ results for all batches

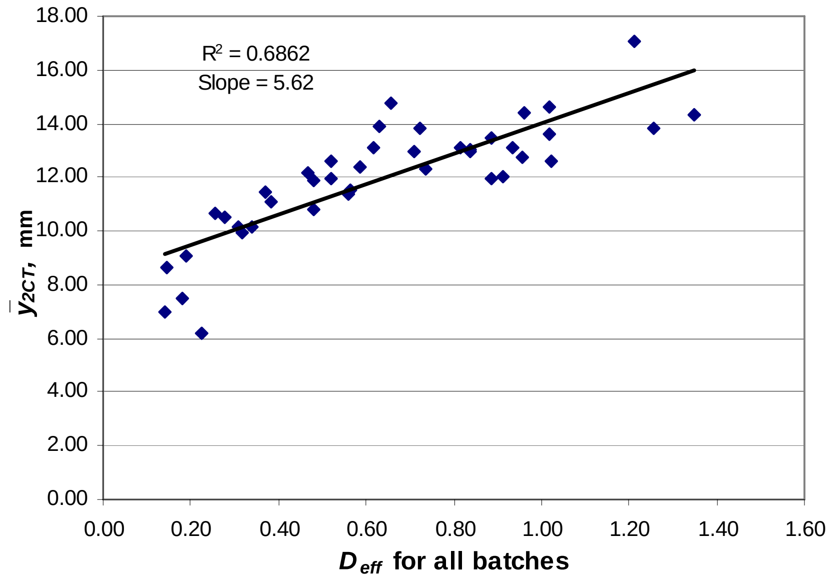


Fig 3.4 Comparison of D_{eff} versus $\overline{y}_{2CT}$ for all batches

3.8 INTERPRETATION OF RESULTS

The results for each test program (Sections 3.9–3.15) include plots of the chloride profiles modeled using Fick's equation with one apparent surface concentration (described in Section 3.5.3), the average depth at twice the corrosion thresholds $\overline{y}_{2CT}$, and the effective diffusion coefficients D_{eff} as measures of concrete permeability. Differences in $\overline{y}_{2CT}$ and D_{eff} for the various concrete mixtures are analyzed using the Student's t-test (covered in Section 3.6) to determine whether the differences are statistically significant.

Plots of the Fick's profiles and $\overline{y}_{2CT}$ provide a visualization of the overall performance of the concretes resistance to chloride penetration. A Fick's profile that exhibits chloride concentrations that decrease rapidly near the specimen surface and has low chloride concentrations at deeper sample depths indicates better resistance to chloride penetration than a profile that exhibits chloride concentrations that decrease gradually, which indicates that the concrete allows deeper penetration of the chlorides. Generally, a large chloride concentration gradient exists near the surface of the concrete specimens. Concrete with low permeability tends to have a higher surface concentration due to chloride build-up near the surface. A Fick's profile that lies below another profile (lower modeled values of chloride concentration) indicates lower permeability and better resistance to chloride penetration.

The average depth of chloride penetration at twice the corrosion threshold $\overline{y}_{2CT}$ represents the depth in the specimens below which the chloride concentration is less than twice the corrosion threshold. The $\overline{y}_{2CT}$ parameter is significant because it provides a direct measure of chloride penetration into concrete, whereas the D_{eff} parameter is a general representation of overall concrete permeability. When comparing $\overline{y}_{2CT}$ values, the concrete with the $\overline{y}_{2CT}$ closest to the surface (smallest value) has the lowest chloride concentrations for all depths deeper than that point, indicating the best protection from chlorides.

3.9 PROGRAM 1 – PASTE CONTENT

Program 1 includes four sets of concrete mixtures that are used to examine the effect of paste content on the resistance to chloride penetration. Each set compares two paste contents with the same *w/cm* ratio, type of cementitious materials, and curing period. The mixtures in this program contain a volume of cementitious material equivalent to 318 kg/m^3 (535 lb/yd^3) of cement or less, with paste contents ranging from 20.5% to 24.2%. It is important to note that the cementitious material and paste contents of these mixtures are lower than industry standards for bridge decks. For example, the Kansas Department of Transportation standard bridge deck mixture contains 358 kg/m^3 (602 lb/yd^3) of cement and 26.9% paste. Additional Program 1 details are provided in Section 2.7.1, and mixture proportions, plastic concrete properties and compressive strengths are provided in Appendix A.

A summary of Program 1 is provided in Table 3.5. The concrete in sets 1 and 2 contain only Type I/II portland cement. The concrete mixtures in set 3 are binary mixtures containing 60%[1] Grade 120 ground granulated blast furnace slag (GGBFS), and the concrete mixtures in set 4 are ternary mixtures containing 60% Grade 120 GGBFS and 6% silica fume (SF).

When one parameter is changed in concrete, there is invariably at least one other parameter that is changed as well. It is important, therefore, to keep in mind all the parameters affected by a single change and potential domino effects in concrete properties. For this program, the paste content is varied by reducing the volume of paste and replacing it with an equivalent volume of aggregate. Therefore,

Table 3.5 Program 1 – Summary

Set	Cementitious Material	*w/cm*	Paste Content, %
1	100% Portland Cement	0.42	23.3 21.6
2	100% Portland Cement	0.45	24.2 22.5
3	Binary (60% G120 GGBFS)	0.42	23.2 21.6
4	Ternary (60% G120 GGBFS 6% SF)	0.42	21.6 20.5

the effect of paste content on the permeability is influenced not only by the properties of the paste, but also by the properties of the aggregate and the interfacial transition zone (ITZ) between the bulk paste and the aggregate. The limestone coarse aggregate used is relatively porous with an absorption of 2.8–3.0% and a specific gravity of approximately 2.58. Increasing aggregate content also increases the volume of ITZ in the mixture and magnifies the effects of the ITZ properties on permeability.

It is generally understood that the ITZ has higher porosity (and lower density) and larger pores than bulk cement paste, due to the "wall effect" phenomenon. Cement particles do not pack as efficiently around a "wall" (the aggregate surface) as they do in the bulk cement paste. As a result, the ITZ can have a higher local *w/cm* ratio and less calcium silicate hydrate (C-S-H) reaction product. The voids in the ITZ close to the aggregate surface are often filled with calcium hydroxide crystals or

[1] As described in Section 2.6, percentage replacements of cement are reported on a volume basis.

ettringite. The higher porosity and larger pores of the ITZ strongly influence the permeability of the concrete as a whole.

Currently, the most effective method for improving the ITZ properties is to densify it with the addition of silica fume in the concrete. Silica fume particles are approximately 200 times smaller than portland cement particles, allowing them to fill the voids in the ITZ. The pozzolanic reaction also reduces the growth of calcium hydroxide crystals in the ITZ because the silica fume reacts with the calcium hydroxide, forming more C-S-H. In general, we would expect the addition of silica fume to result in a decrease in permeability. This is consistent with the results seen in this program.

The use of GGBFS in concrete is generally understood to reduce concrete permeability. The rate of hydration (producing C-S-H) for slag is much slower than for portland cement or pozzolans. The heat of hydration for GGBFS is also lower than for portland cement, so GGBFS can also be used to control the thermal properties of concrete.

In general, the results of Program 1 indicate that reductions in paste content for concrete containing only portland cement (sets 1 and 2) clearly result in increased permeability and chloride penetration. For concrete containing mineral admixtures (sets 3 and 4), changes in permeability resulting from changes in paste content were not clearly seen.

3.9.1 Program 1 Sets 1 and 2 (100% Type I/II Portland Cement, 0.42 and 0.45 *w/cm* ratio)

For the concrete in set 1 (*w/cm* ratio = 0.42), the Fick's profile for the concrete containing 23.3% paste has a higher surface concentration than the concrete containing 21.5% paste, as shown in Fig. 3.5. The chloride concentrations for the concrete containing 23.3% paste drop below the levels for the 21.6% paste concrete at a depth of approximately 4 mm (0.16 in.), indicating better protection from chloride penetration at the deeper levels. The $\overline{y}_{2CT}$ for the 23.3% mix occurs at a shallower

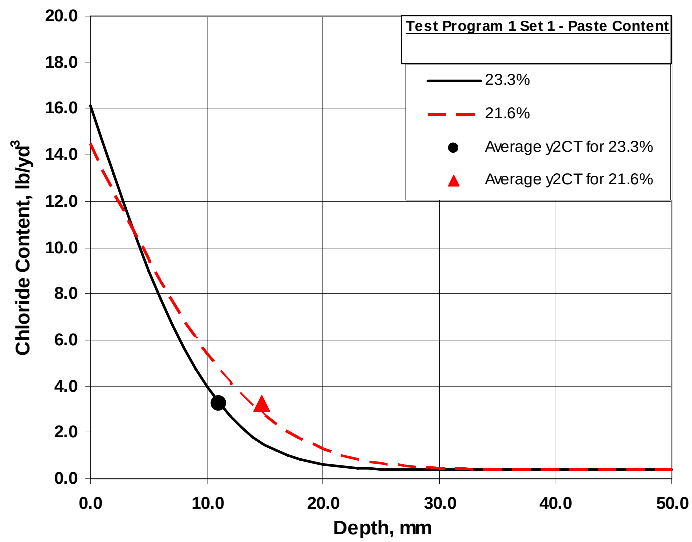


Fig. 3.5 Program 1 Set 1 Fick's profiles and $\overline{y}_{2CT}$ for concrete with *w/cm* ratio of 0.42 containing 23.3% and 21.6% paste

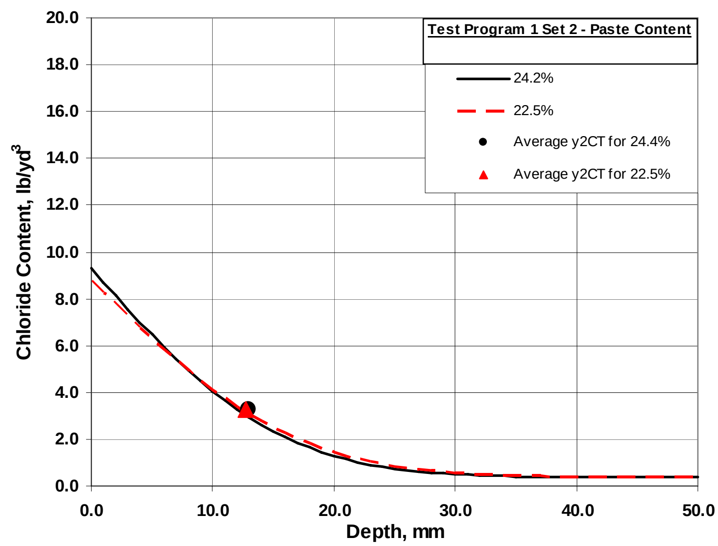


Fig. 3.6 Program 1 Set 2 Fick's profiles and $\overline{y}_{2CT}$ for concrete with *w/cm* ratio of 0.45 containing 24.2% and 22.5% paste

depth than for the 21.6% mix (Fig. 3.5), also indicating better resistance to chloride penetration.

For the concrete in set 2 (*w/cm* ratio = 0.45), the two Fick's profiles and $\overline{y}_{2CT}$ values are nearly identical, indicating similar chloride resistance performance as shown in Fig. 3.6.

The individual Fick's profiles and the y_{2CT} for the concrete batches in set 1 are presented in Figs. B.28 and B.39, and for set 2 in Figs. B.3 and B.7 in Appendix B.

The D_{eff} and $\overline{y}_{2CT}$ results for sets 1 and 2 are presented graphically in Figs. 3.7 and 3.8.

For set 1 (*w/cm* ratio = 0.42), the decrease in the paste content from 23.3% to 21.6% resulted in an increase in the D_{eff} from 0.38 to 0.65 mm^2/day and an increase in the $\overline{y}_{2CT}$ from 11.1 to 14.8 mm (0.44 to 0.58 in.). For set 1, the results for both performance measures (the D_{eff} and $\overline{y}_{2CT}$) indicate an increase in permeability with decreased paste and are statistically significant ($\alpha = 0.01$) (Table 3.6).

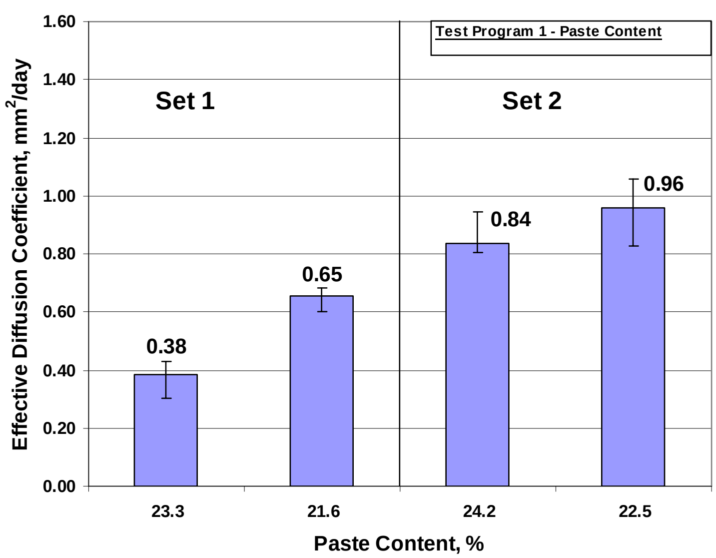


Fig. 3.7 Program 1 Sets 1 and 2 Effective Diffusion Coefficients versus Paste Content for concrete containing 318 kg/m^3 (535 lb/yd^3) of 100% Type I/II portland cement. The concrete in set 1 has a *w/cm* ratio of 0.42 and a 14-day curing period. The concrete in set 2 concrete has a *w/cm* ratio of 0.45 and a 7-day curing period.

For set 2 (*w/cm* ratio = 0.45), the decrease in the paste content from 24.2% to 22.5% resulted in an increase in the D_{eff} from 0.84 to 0.96 mm^2/day, indicating a reduction in permeability. In contrast, the decrease in paste content resulted in a slight decrease in the $\overline{y}_{2CT}$ from 13.0 to 12.8 mm (0.51 to 0.50 in.). The differences for both performance measures are not statistically significant (Table 3.7) and therefore the trend is unclear for set 2. If only the D_{eff} results are considered, since the D_{eff} is as a more general indicator of concrete performance for all depths, the results for set 2 may indicate a slight bias toward reduced paste contents correlating with an increase in permeability.

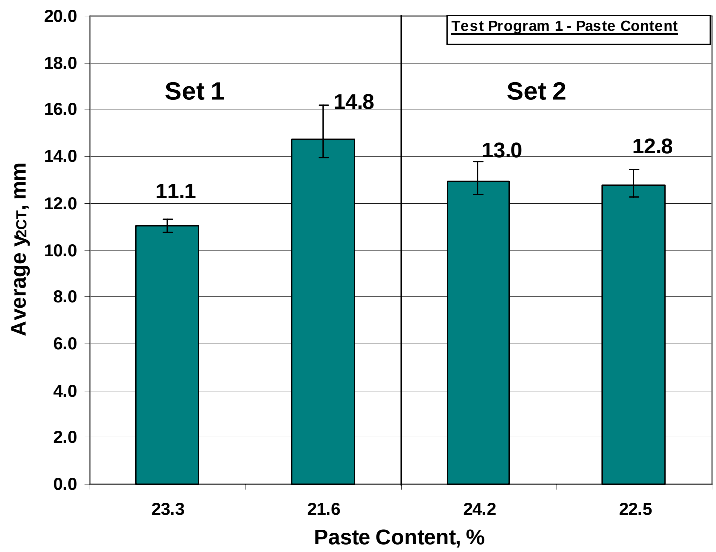


Fig. 3.8 Program 1 Sets 1 and 2 $\overline{y}_{2CT}$ versus Paste Content for concrete containing 318 kg/m³ (535 lb/yd³) of 100% Type I/II portland cement. The concrete in set 1 has a *w/cm* ratio of 0.42 and a 14-day curing period. The concrete in set 2 concrete has a *w/cm* ratio of 0.45 and a 7-day curing period.

Table 3.6 Student's t-Test Results for Program 1 Set 1

	Paste Content, %	D_{eff}	Paste Content, %		$\overline{y}_{2CT}$, mm	Paste Content, %	
			23.3	21.6		23.3	21.6
Paste Content	23.3	0.38		Y 0.01 (99%)	11.1		Y 0.01 (99%)
	21.6	0.65			14.8		

Note: For the results of the Student's t-tests, "Y α (CI)" indicates a statistical difference between the two samples at a significance level of α and a confidence interval (CI) of 100 × (1−α). "N" indicates that there is no statistical difference at the highest considered significance level, α = 0.20 (80%).

Though it is not possible to compare between sets 1 and 2 because of differences in *w/cm* ratio, curing period, and drying times (discussed in Section 3.7.1), the apparent reduction in sensitivity of set 2 to the paste content raises the question of whether reduced curing or increased *w/cm* ratio (14 days and 0.42 for set 1 versus 7 days and 0.45 for set 2), make concrete permeability less sensitive to changes in paste content.

In general, the results for Program 1 sets 1 and 2 indicate that a reduction in paste content results in increased permeability and decreased resistance to chloride penetration.

Table 3.7 Student's t-Test Results for Program 1 Set 2

	Paste Content, %	D_{eff}	Paste Content, %		$\overline{y}_{2CT}$, mm	Paste Content, %	
			24.2	**22.5**		**24.2**	**22.5**
Paste Content	**24.2**	0.84		N	13.0		N
	22.5	0.96			12.8		

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

3.9.2 Program 1 Set 3 (60% Grade 120 GGBFS, 0.42 *w/cm* ratio)

For the concrete in Program 1 set 3, Fick's profile for the concrete containing 23.2% paste has a higher surface concentration than the concrete containing 21.6% paste, as shown in Fig. 3.9. The surface concentrations for both mixtures are relatively high, approximately 20 and 16 lb/yd^3, respectively. The chloride concentrations for the concrete containing 21.6% paste remains below the concrete containing 23.2% paste throughout the test's range of depths. Contrary to expectation, this suggests the batch with the lower paste content performed better than the concrete with the higher paste content. The $\overline{y}_{2CT}$ results are nearly identical, indicating similar performance. The individual Fick's profiles and y_{2CT} for the two concrete batches in set 3 are presented in Figs. B.29 and B.30 in Appendix B.

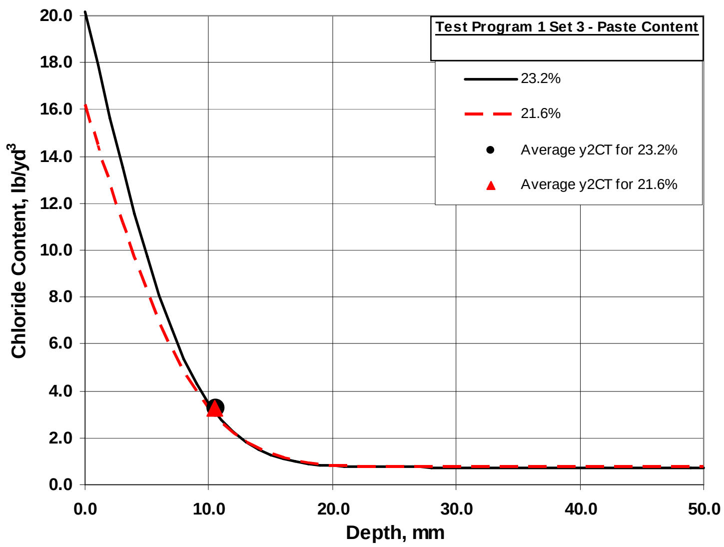


Fig. 3.9 Program 1 Set 3 Fick's profiles and $\overline{y}_{2CT}$ for concrete containing 23.2% and 21.6% paste

D_{eff} and $\overline{y}_{2CT}$ for set 3 are presented graphically in Figs. 3.10 and 3.11. For the concrete mixtures containing 60% Grade 120 GGBFS, a decrease in paste content from 23.3% to 21.6% resulted in a slight increase in the D_{eff} from 0.26 to 0.28 mm^2/day and a slight decrease in the $\overline{y}_{2CT}$ from 10.6 to 10.5 mm (0.42 to 0.41 in.). The differences are not statistically significant for either parameter (Table 3.8), so the trend is unclear for the binary mixtures in set 3.

3.9.3 Program 1 Set 4 (60% Grade 120 GGBFS, 6% SF, 0.42 *w/cm* ratio)

For the concrete in Program 1 set 4, the Fick's profile for the concrete containing 21.6% paste has a higher surface concentration than the concrete containing 20.5% paste (Fig. 3.12). The chloride concentrations for the concrete containing 20.5% paste remain below the concentrations for the concrete containing 21.6% paste throughout the test's depth range and also has a lower background chloride concentration, as shown in Fig. 3.12. This indicates that for these ternary mixtures, the batch with the lower paste content performed slightly better than the concrete with the higher paste content. $\overline{y}_{2CT}$ for the concrete with 20.5% paste was

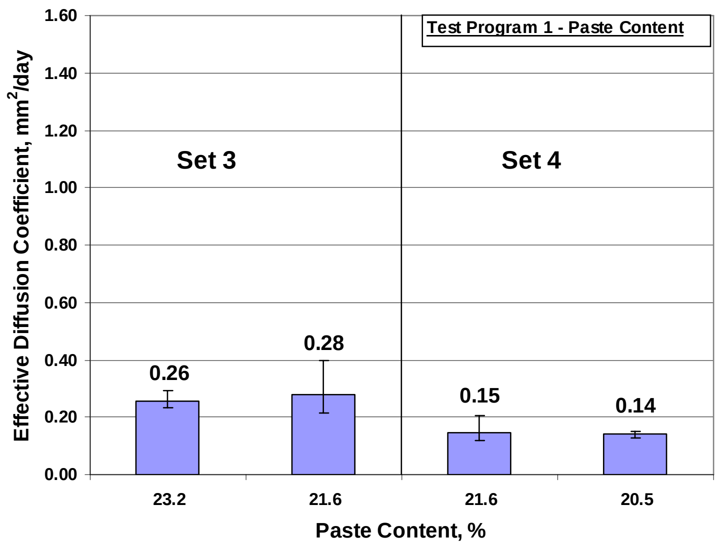


Fig. 3.10 Program 1 Sets 3 and 4 Effective Diffusion Coefficients versus Paste Content for concrete with *w/cm* ratio of 0.42, a cementitious materials factor of 318 kg/m^3 (535 lb/yd^3) and a 14-day curing period. The concrete in set 3 contains 60% Grade 120 GGBFS. The concrete in set 4 concrete contains 60% Grade 120 GGBFS and 6% SF.

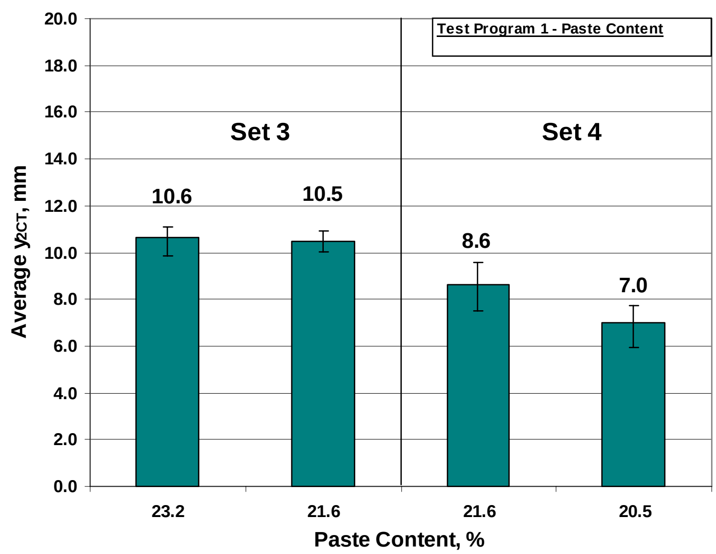


Fig. 3.11 Program 1 Sets 3 and 4 $\overline{y}_{2CT}$ versus Paste Content for concrete with *w/cm* ratio of 0.42, a cementitious materials factor of 318 kg/m^3 (535 lb/yd^3) and a 14-day curing period. The concrete in set 3 contains 60% Grade 120 GGBFS. The concrete in set 4 concrete contains 60% Grade 120 GGBFS and 6% SF.

smaller (shallower) than the concrete with 21.6% paste, indicating the reduction in paste content resulted in better protection from chloride penetration. Fick's profiles and y_{2CT} for the individual specimens in the two concrete batches in Program 1 set 4 are presented in Figs. B.31 and B.32 in Appendix B.

Table 3.8 Student's t-Test Results for Program 1 Set 3

	Paste Content, %	D_{eff}	Paste Content, % 23.2	Paste Content, % 21.6	$\overline{y}_{2CT}$, mm	Paste Content, % 23.2	Paste Content, % 21.6
Paste Content	23.2	0.26		N	10.6		N
Paste Content	21.6	0.28			10.5		

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

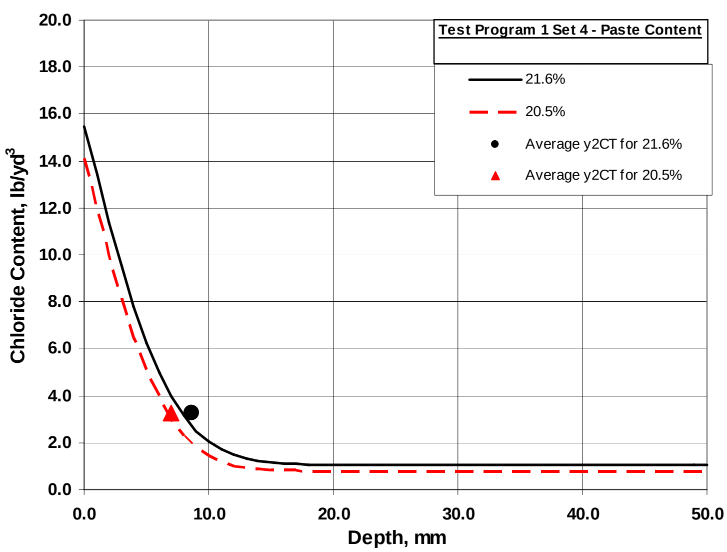


Fig. 3.12 Program 1 Set 4 Fick's profiles and $\overline{y}_{2CT}$ for concrete containing 21.6% and 20.5% paste

The effective diffusion coefficients and $\overline{y}_{2CT}$ for Program 1 set 4 are presented graphically in Figs. 3.10 and 3.11. For concretes containing 60% Grade 120 GGBFS and 6% SF, the decrease in paste content from 21.6% to 20.5% resulted in a slight decreases in the D_{eff} from 0.15 to 0.14 mm^2/day and in the $\overline{y}_{2CT}$ from 8.6 to 7.0 mm (0.34 to 0.28 in.). D_{eff} for both mixtures is very low. Both parameters indicate that decreased levels of paste content correspond with better resistance to chloride penetration. The differences in D_{eff} are not statistically significant (Table 3.9), whereas the differences in the $\overline{y}_{2CT}$ are statistically significant at a confidence level of $\alpha = 0.11$ (89%). Program 1 set 4 results indicate that for the ternary mixtures in this set, resistance to chloride penetration is enhanced with a reduction in paste content.

Table 3.9 Student's t-Test Results for Program 1 Set 4

	Paste Content, %	$\boldsymbol{D_{eff}}$	**Paste Content, %**		$\boldsymbol{\overline{y}_{2CT}}$**, mm**	**Paste Content, %**	
			21.6	**20.5**		**21.6**	**20.5**
Paste Content	**21.6**	0.15		N	8.6		Y 0.11 (89%)
	20.5	0.14			7.0		

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

An alternate solution was also considered in this analysis. Fig. B.31 shows the data for the 21.6% paste mixture (Batch 354). In the original analysis, only three non-standard sample depths were used instead of the standard 5 sample depths because the samples from standard depths had been lost during laboratory chloride testing. In the alternative solution, specimen A was discarded from the analysis and the set 4 results are slightly different. In the original analysis, the surface concentration for specimen A was significantly higher than for specimen B and C. It is apparent in Fig. B.31 that this may be caused by the lack of test results for the standard 1–3 mm (0.04–0.1 in.) depth. As a replacement in the original analysis, the 3–5 mm (0.1–0.2 in.) depth was used. Extrapolation to a surface concentration from a lower depth (farther from the surface), inevitably caused greater error than if the 1–3 mm (0.04–0.1 in.) sample had been available. The results from the alternate solution, discarding specimen A from the analysis, indicate that D_{eff} is 0.13 mm^2/day and $\overline{y}_{2CT}$ is 8.2 mm (0.32 in.). In this case, there is no statistical difference between the 21.6% and the 20.5% paste mixtures for either parameter. The general trends in the results also more closely follow expectations, change with D_{eff} increasing slightly from 0.13

to 0.14 mm^2/day with the decreased paste content. The $\overline{y}_{2CT}$ decreases with decreased paste content, from 8.2 to 7.0 mm (0.32 to 0.28 in.), not following the expected trend, but the differences are not statistically significant. In the alternate analysis, the final result is that the ternary mixtures with GGBFS and silica fume exhibited no statistical difference in permeability for paste contents of 21.6% and 20.5%.

3.9.4 Program 1 Summary

For mixtures containing 100% portland cement, results generally indicate that decreases in paste content result in reduced resistance to chloride penetration. A reduction in paste content was achieved by replacing paste with aggregate while maintaining a constant maximum aggregate size of 25 mm (1 in.). This resulted in an increase the surface area of aggregate and an increase in the total volume of ITZ in the mixture. Because the ITZ is the portion of the mixture responsible for most of the moisture movement, it is reasonable that an increase in the ITZ volume would result in increased flow of moisture and salt during testing and an overall reduction in resistance to chloride penetrability. Therefore, for 100% portland cement mixtures, a reduction in paste content resulted in an increase in chloride penetrability.

The picture is less clear for those mixtures containing mineral admixtures. For the binary and ternary mixtures in sets 3 and 4, the diffusion coefficients were lower than for the sets 1 and 2 mixtures containing 100% portland cement, indicating that the presence of mineral admixtures generally reduced the permeability, as expected. The results for concrete containing a mineral admixture did not exhibit clear trends. The presence of mineral admixtures, which is known to enhance the concrete's ability to resist chloride penetration, dominates the overall permeability performance but apparently made the concrete performance less sensitive to minor changes in paste content at these low paste content levels.

3.10 PROGRAM 2 – CURING PERIOD

Program 2 includes eight sets of concrete mixtures examining the effect of curing period on the resistance to chloride penetration. Each set compares multiple curing periods for concrete with constant paste content, *w/c* ratio, and type of cementitious material. Curing periods include 7, 14, and 28 days. Several of the sets have a companion set with an identical mix design, except that the concrete contains a different type of cement. The types of cement used in this program include Type I/II, coarse ground Type II, and medium ground Type II. Details about the cement used in this study are provided in Section 2.2.1. All sets contain only portland cement; no mineral admixtures are used for this program. All sets contain mixtures with a paste content of 24.4% or less and *w/c* ratios of 0.41, 0.43 or 0.45. Mixture proportions, plastic concrete properties, and compressive strengths are provided in Appendix A.

A summary of Program 2 is provided in Table 3.10. The concrete in sets 1 and 2 have a *w/c* ratio of 0.45 and paste contents of 24.2% and 24.4%, respectively. Set 1 contains Type I/II cement, while set 2 contains coarse ground Type II cement.

Table 3.10 Program 2 – Summary

Set	Cement Type	*w/c*	Paste Content, %	Curing Period, days
1	I/II	0.45	24.2	7 14
2	C.G.† II	0.45	24.4	7 14 28
3	I/II	0.41	23.1	7 14
4	M.G.†† II	0.41	23.1	7 14
5	I/II	0.43	23.7	7 14
6	M.G.†† II	0.43	23.7	7 14
7	I/II	0.45	24.4	7 14
8	M.G.†† II	0.45	24.4	7 14

†C.G. = Coarse Ground ††M.G.= Medium Ground

Comparisons between sets 1 and 2 cannot be made because they have different drying times after the curing period, as discussed in Section 3.7.1. Companion sets 3 and 4, 5 and 6, and 7 and 8 include Type I/II cement and medium ground Type II cement, respectively. The concrete in sets 3 and 4 have a *w/c* ratio of 0.41, and a paste content of 23.1%. The concrete in sets 5 and 6 have a *w/c* ratio of 0.43, and a paste content of 23.7%. The concrete in sets 7 and 8 have a *w/c* ratio of 0.45, and a paste content of 24.4%. Additional Program 2 details are provided in Section 2.7.1, and mixture proportions, plastic concrete properties, and compressive strengths are provided in Appendix A.

As discussed in Section 1.6, the length of curing is an important parameter affecting concrete permeability and the ability of concrete to resist chloride penetration. Generally, chloride diffusion is reduced as the curing period increases. A minimum of 7 days continuous wet curing is required to achieve a discontinuous capillary pore system for a concrete with a *w/c* ratio of 0.45 (Mindess et. al 2003). For this study, a minimum of fourteen days wet curing is recommended for concrete bridge decks to reduce shrinkage and minimize cracking. In the companion report to this study, Lindquist et al. (2008) examine the effect of the length of the curing period on free shrinkage and the effect on cracking in LC-HPC bridge decks. This study examines the effect of extended curing, from 7 to 14 days, and up to 28 days in one case, on the resistance of LC-HPC concrete mixtures to chloride penetration. The results are in general agreement with the expected trend that extended curing decreases chloride penetrability.

3.10.1 Program 2 Set 1 (24.2% Paste, 100% Type I/II Portland Cement, 0.45 *w/c* ratio)

For the concrete in set 1, the Fick's profiles are nearly identical. The profile for concrete with 14-days of curing exhibits a slightly lower surface chloride concentration than do the concretes with 7-day curing. The $\overline{y}_{2CT}$ values for the three mixtures are nearly identical. The Fick's profiles and $\overline{y}_{2CT}$ for set 1 are presented in

Fig. 3.13. The individual Fick's profiles and y_{2CT} for the batches in Program 2 set 1 are presented in Figs. B.3, B.4 and B.8 in Appendix B.

The D_{eff} and $\overline{y}_{2CT}$ for set 1 are presented graphically in Figs. 3.14 and 3.15.

The two batches with 7-day curing periods had the same values for D_{eff} (0.84 and 0.84 mm^2/day) and nearly identical results for $\overline{y}_{2CT}$ (13.0 and 13.1 mm)(0.51 and 0.52 in.). Unexpectedly, the concrete with a 14-day curing period had a higher D_{eff} (0.93 mm^2/day) than the concrete cured for 7 days, suggesting higher permeability, and $\overline{y}_{2CT}$ of 13.1 mm (0.52 in.), closely matching the results for the concretes cured for 7 days. None of the differences in the results are statistically significant (Table 3.11), indicating no change in permeability with increased curing.

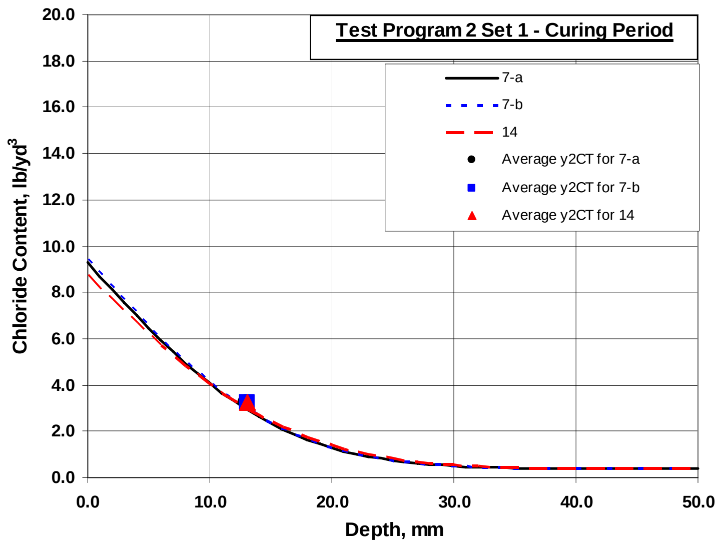


Fig. 3.13 Program 2 Set 1 Fick's profiles and $\overline{y}_{2CT}$ for concrete cured for 7 and 14 days

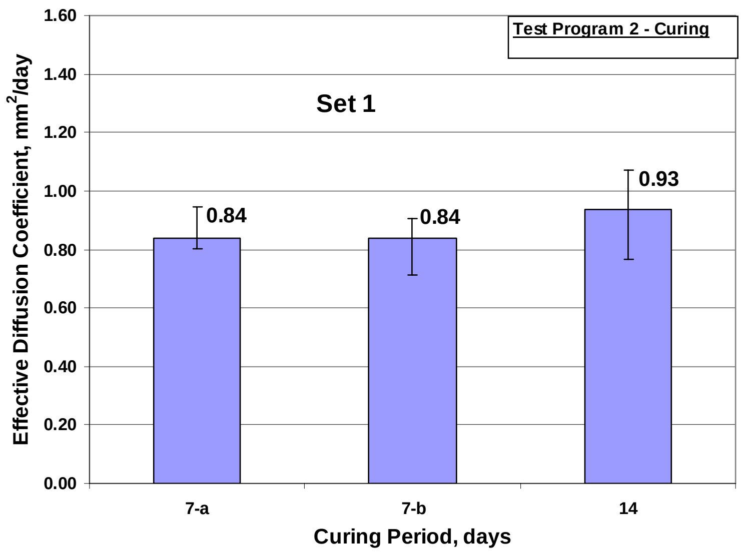


Fig. 3.14 Program 2 Set 1 Effective Diffusion Coefficients versus Curing Period for concrete with *w/c* ratio of 0.45, 318 kg/m^3 (535 lb/yd^3) Type I/II portland cement, and paste content of 24.2%

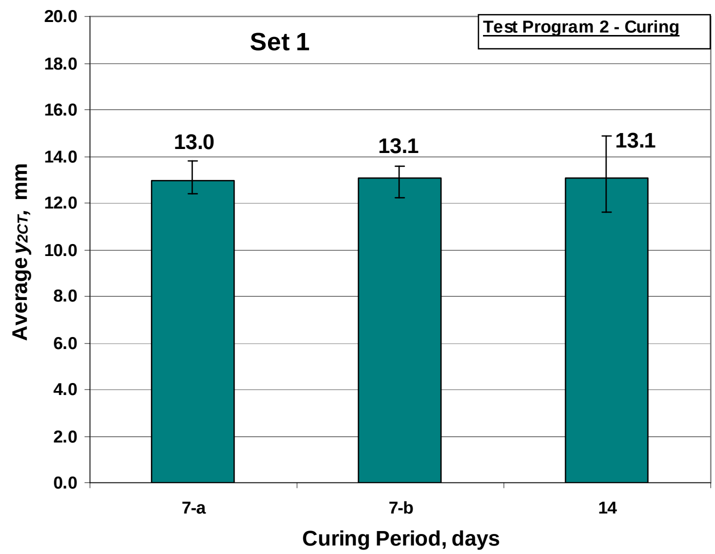


Fig. 3.15 Program 2 Set 1 $\overline{y}_{2CT}$ for concrete with *w/c* ratio of 0.45, 318 kg/m^3 (535 lb/yd^3) Type I/II portland cement, and paste content of 24.2%

Table 3.11 Student's t-Test Results for Program 2 Set 1

	Curing Period, days	D_{eff}	Curing Period, days			$\overline{y}_{2CT}$, mm	Curing Period, days		
			7-a	7-b	14		7-a	7-b	14
Curing Period	7-a	0.84		N	N	13.0		N	N
	7-b	0.84			N	13.1			N
	14	0.93				13.1			

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

3.10.2 Program 2 Set 2 (24.2% Paste, 100% Coarse Ground Type II Portland Cement, 0.45 *w/c* ratio)

For the concrete in Program 2 set 2, the Fick's profile for the concrete cured for 28 days has the lowest chloride concentrations for all depths greater than approximately 3 mm (0.12 in.), followed by the profile of the concrete cured for 14 days for all depths greater than approximately 7 mm (0.28 in.). The profiles for the concretes cured for 7 days have the highest chloride concentrations, suggesting the highest permeability. The trend is consistent, indicating greater protection from chloride penetration with longer curing periods. The same trend is exhibited by the $\overline{y}_{2CT}$ results, with progressively lower values of $\overline{y}_{2CT}$, with increased curing periods. The Fick's profile and $\overline{y}_{2CT}$ for the four concrete batches in set 2 are presented in Fig. 3.16. The individual Fick's profiles and y_{2CT} are provided in Figs. B.5, B.9, B.10 and B.11 in Appendix B.

The D_{eff} and $\overline{y}_{2CT}$ for set 2 are presented graphically in Figs. 3.17 and 3.18. The results for both performance measures indicate that increasing the curing period results in decreased chloride penetration.

The concretes cured for 7 days had D_{eff} values of 1.35 and 1.26 mm^2/day, with an average of 1.31 mm^2/day. Curing for 14 days resulted in a reduction in the D_{eff} to 1.02 mm^2/day, and curing for an additional 14 days (28 days curing total) resulted in an additional reduction in the D_{eff} to 0.91 mm^2/day. The differences in the D_{eff} results are statistically significant for the two concretes cured for 7 days and the concrete cured for 28 days at α values of 0.01 (99%) and 0.06 (94%), as shown in Table 3.12a.

The difference between the D_{eff} values for the concrete cured for 7 days (D_{eff} = 1.35 mm^2/day)(Fig. 3.17) and the concrete cured for 14 days is also statistically significant at $\alpha = 0.05$ (95%).

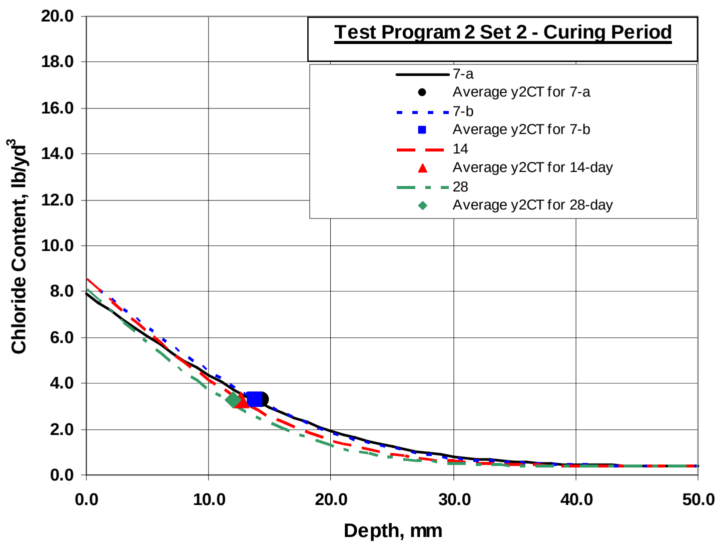


Fig. 3.16 Program 2 Set 2 Fick's profiles and $\overline{y}_{2CT}$ for concrete cured for 7, 14 and 28 days

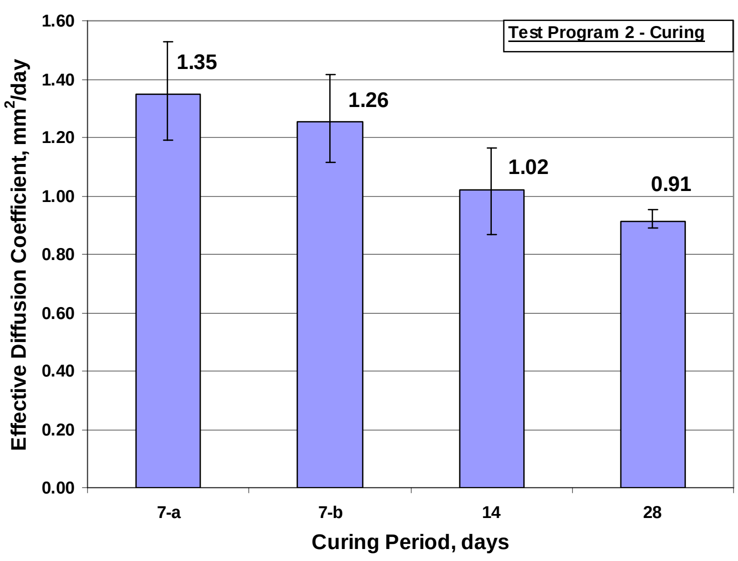


Fig. 3.17 Program 2 Set 2 Effective Diffusion Coefficients versus Curing Period for concrete with 24.2% paste, a *w/c* ratio of 0.45, 318 kg/m^3 (535 lb/yd^3) coarse ground Type II portland cement, and paste content of 24.2%

The concretes cured for 7 days had $\overline{y}_{2CT}$ values of 14.4 and 13.8 mm (0.57 and 0.54 in.) with an average of 14.1 mm (0.56 in.). Curing for 14 days resulted in a reduction in the $\overline{y}_{2CT}$ to 12.6 mm (0.50 in.). Curing for an additional 14 days (28 days curing total) resulted in an additional reduction in $\overline{y}_{2CT}$ to 12.0 mm (0.47 in.). The differences in the $\overline{y}_{2CT}$ results are statistically significant for the concrete cured for 7 days and the concrete cured for 28 days at α values of 0.01 (99%) and 0.06 (94%) as shown in Table 3.12b. The difference between the $\overline{y}_{2CT}$ values for the concrete cured for 7 days with $\overline{y}_{2CT}$ = 14.4 mm (0.57 in.)(Fig. 3.18) and the concrete cured for 14 days is also statistically significant at α = 0.04 (96%).

Overall, the set 2 performance measures are consistent and clearly indicate that increasing the curing period results in the reduction of chloride penetration.

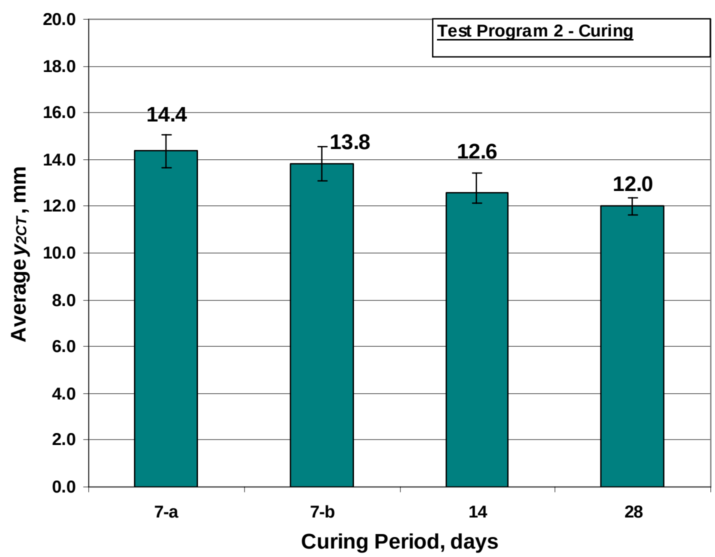


Fig. 3.18 Program 2 Set 2 $\overline{y}_{2CT}$ versus Curing Period for concrete with 24.2% paste, a *w/c* ratio of 0.45, 318 kg/m^3 (535 lb/yd^3) coarse ground Type II portland cement, and paste content of 24.2%

Table 3.12 Student's t-Test Results for Program 2 Set 2

(a) D_{eff}

	Curing Period, days	D_{eff}	Curing Period, days			
			7-a	7-b	14	28
Curing Period	7-a	1.35		N	Y 0.05 (95%)	Y 0.01 (99%)
	7-b	1.26			N	Y 0.06 (94%)
	14	1.02				N
	28	0.91				

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

(b) $\overline{y}_{2CT}$

	Curing Period, days	$\overline{y}_{2CT}$, mm	Curing Period, days			
			7-a	7-b	14	28
Curing Period	7-a	14.4		N	Y 0.04 (96%)	Y 0.01 (99%)
	7-b	13.8			N	Y 0.06 (94%)
	14	12.6				N
	28	12.0				

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

3.10.3 Program 2 Sets 3 and 4 (23.1% Paste, 0.41 *w/c* ratio, and 100% Type I/II or Medium Ground Type II Portland Cement)

The concrete in Program 2 set 3 includes Type I/II portland cement, while the concrete in set 4 includes medium ground Type II cement. For set 3 (concrete containing Type I/II cement), the Fick's profile (Fig. 3.19) for the concrete cured for 14 days has lower chloride concentrations than the concrete cured 7 days for depths below 4 mm (0.16 in.). The same trend is also apparent in Fig. 3.20 for concrete containing medium ground Type II cement. In the latter case, the profile for the set 4 concrete cured for 14 days dips even farther below the 7-day profile, indicating a greater benefit from the extended curing for the concrete containing medium ground Type II cement. For both sets 3 and 4, $\overline{y}_{2CT}$ is shallower for the concretes cured for 14 days than for the concretes cured for 7 days. These results indicate reduced permeability and increased protection from chloride penetration with increasing curing period.

The individual Fick's profiles and y_{2CT} for set 3 are provided in Figs. B.12 and B.13, and for set 4 in Figs. B.18 and B.19 in Appendix B.

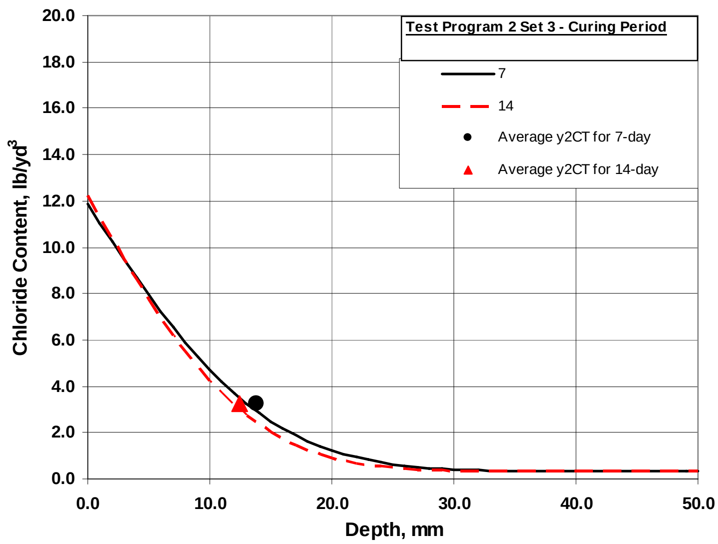


Fig. 3.19 Program 2 Set 3 Fick's profiles and $\overline{y}_{2CT}$ for concrete with Type I/II cement and cured for 7 or 14 days

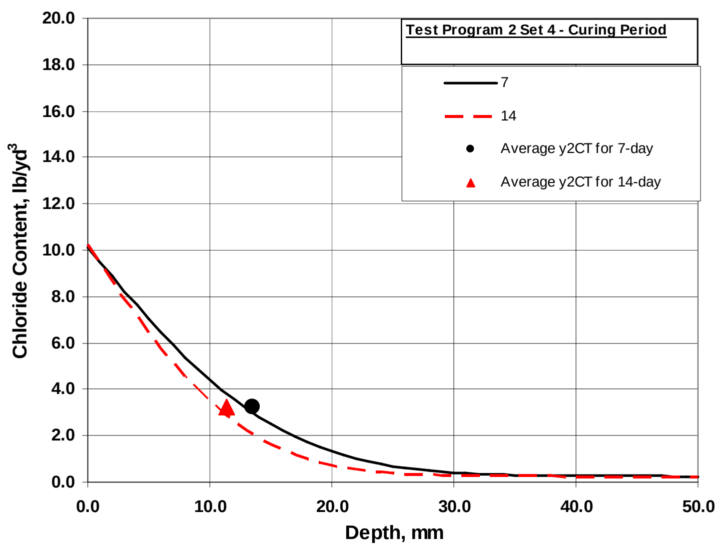


Fig. 3.20 Program 2 Set 4 Fick's profiles and $\overline{y}_{2CT}$ for concrete with medium ground Type II cement and cured for 7 or 14 days

The D_{eff} and $\overline{y}_{2CT}$ for sets 3 and 4 are presented graphically in Figs. 3.21 and 3.22. The results for both performance measures indicate that increasing the curing period from 7 days to 14 days results in decreased chloride penetration.

For the concrete made with Type I/II cement (set 3), increasing the curing period from 7 to 14 days decreased D_{eff} from 0.72 to 0.59 mm^2/day. This difference is statistically significant at a confidence level of α = 0.19 (81%) (Table 3.13). The D_{eff} of the concrete made with medium ground Type II cement (set 4) decreased from 0.88 to 0.56 mm^2/day. Even though the decrease in D_{eff} for set 4 is more than twice that for set 3, it is not statistically significant (Table 3.14) due to the scatter in the test results for the concrete cured for 7 days (see Fig. 3.21).

$\overline{y}_{2CT}$ decreased from 13.8 to 12.4 mm (0.54 to 0.49 in.) for the concrete made with Type I/II cement (set 3), and from 13.5 to 11.4 mm (0.53 to 0.45 in.) for the concrete made with medium ground Type II cement (set 4). The differences in the $\overline{y}_{2CT}$ for set 3 are statistically significant (Table 3.13) but not for set 4 (Table 3.14).

Overall, the D_{eff} and $\overline{y}_{2CT}$ results for sets 3 and 4 suggest improved performance with longer curing and larger gains in protection for the same increase in curing period for the concrete containing medium ground Type II cement.

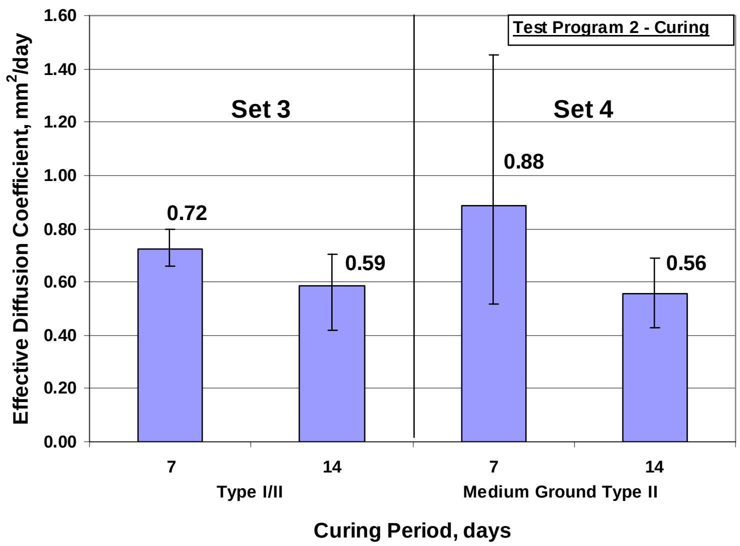


Fig. 3.21 Program 2 Sets 3 and 4 Effective Diffusion Coefficients versus Curing Period for concrete with 23.1% paste, a *w/c* ratio of 0.41, and 318 kg/m^3 (535 lb/yd^3) 100% portland cement. Set 3 concrete contains Type I/II cement. Set 4 concrete contains medium ground Type II cement.

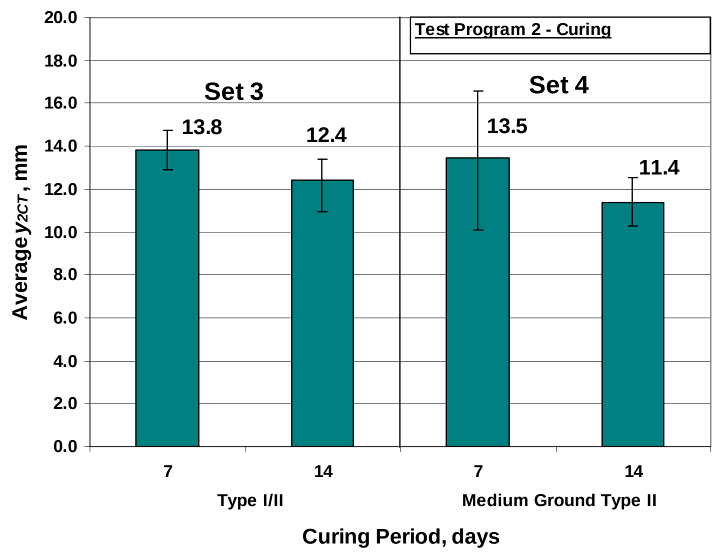


Fig. 3.22 Program 2 Sets 3 and 4 $\overline{y}_{2CT}$ versus Curing Period for concrete with 23.1% paste, a *w/c* ratio of 0.41, and 318 kg/m^3 (535 lb/yd^3) 100% portland cement. Set 3 concrete contains Type I/II cement. Set 4 concrete contains medium ground Type II cement.

Table 3.13 Student's t-Test Results for Program 2 Set 3

	Curing Period, days	D_{eff}	Curing Period, days		$\overline{y}_{2CT}$, mm	Curing Period, days	
			7	14		7	14
Curing Period	7	0.72		Y 0.19 (81%)	13.8		Y 0.20 (80%)
	14	0.59			12.4		

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

Table 3.14 Student's t-Test Results for Program 2 Set 4

	Curing Period, days	D_{eff}	Curing Period, days		$\overline{y}_{2CT}$, mm	Curing Period, days	
			7	14		7	14
Curing Period	7	0.88		N	13.5		N
	14	0.56			11.4		

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

3.10.4 Program 2 Sets 5 and 6 (23.7% paste, 0.43 *w/c* ratio, and either 100% Type I/II or Medium Ground Type II Portland Cement,)

The concrete in Program 2 set 5 contains Type I/II cement, while the concrete in set 6 contains medium ground Type II cement. Contrary to expectations, the Fick's profile for the concrete cured for 14 days is higher than the profile for concrete cured for 7 days for both sets (Figs. 3.23 and 3.24), indicating an increase in permeability with increased curing. The profiles, however, are similar at greater depths, especially for the concrete containing Type I/II cement in set 5. The $\overline{y}_{2CT}$ for the sets follow the same trend as the Fick's profiles, with concrete cured for 14 days exhibiting greater chloride penetration than the concrete cured for 7 days.

The individual Fick's profiles and y_{2CT} for set 5 are provided in Figs. B.14 and B.15, and for set 6 in Figs. B.20 and B.21 in Appendix B.

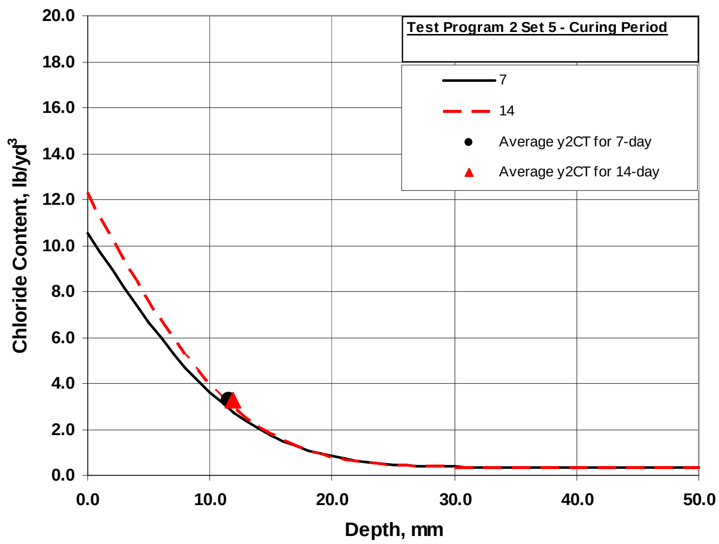


Fig. 3.23 Program 2 Set 5 Fick's profiles and $\overline{y}_{2CT}$ for concrete with Type I/II cement

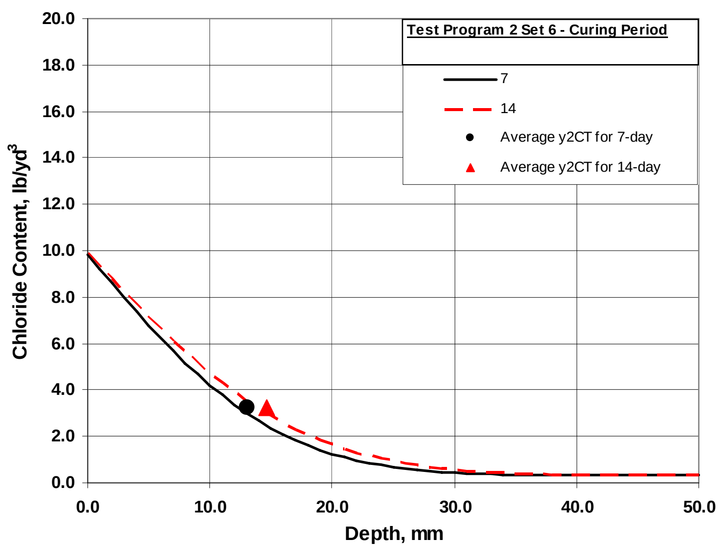


Fig. 3.24 Program 2 Set 6 Fick's profiles and $\overline{y}_{2CT}$ for concrete with medium ground Type II cement

The D_{eff} and $\overline{y}_{2CT}$ for sets 5 and 6 are presented graphically in Figs. 3.25 and 3.26. For the concrete made with Type I/II cement (set 5), D_{eff} decreased from 0.56 to 0.52 mm^2/day, with an increase in curing from 7 to 14 days. Although the difference is not statistically significant (Table 3.22), these results indicate better protection from chloride penetration with longer curing. In contrast, concrete made with medium ground Type II cement (set 6) exhibited an increase in the D_{eff} from 0.82 to 1.02 mm^2/day, with the same increase in curing period. The results for set 6 indicate a statistically significant difference in D_{eff} at a significance level of $\alpha = 0.04$ (96%) (Table 3.23).

$\overline{y}_{2CT}$ increased slightly, from 11.5 to 11.9 mm (0.45 to 0.47 in.), with the increase in curing period for set 5, although the difference is not statistically significant (Table 3.22), indicating no discernable difference in the means. For set 6, the depth increased from 13.1 to 14.6 mm (0.52 to 0.57 in.) with the increase in curing period, also indicating a decrease in protection with longer curing, a result that is statistically significant (Table 3.22) at a confidence level of $\alpha = 0.05$ (95%).

The results for set 5 are unclear, but the results for set 6 clearly show a trend of longer curing resulting in increased permeability. Set 6 results are in direct contrast to expectations that increased curing period results in decreased permeability. These results have no clear explanation other than experimental or random error.

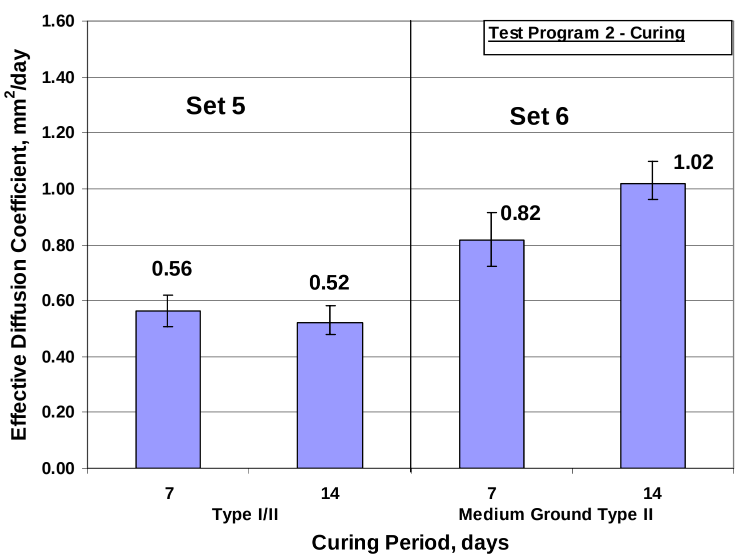


Fig. 3.25 Program 2 Sets 5 and 6 Effective Diffusion Coefficients versus Curing Period for concrete with 23.7% paste, a *w/c* ratio of 0.43, and 318 kg/m^3 (535 lb/yd^3) 100% portland cement. Set 5 concrete contains Type I/II cement. Set 6 concrete contains medium ground Type II cement.

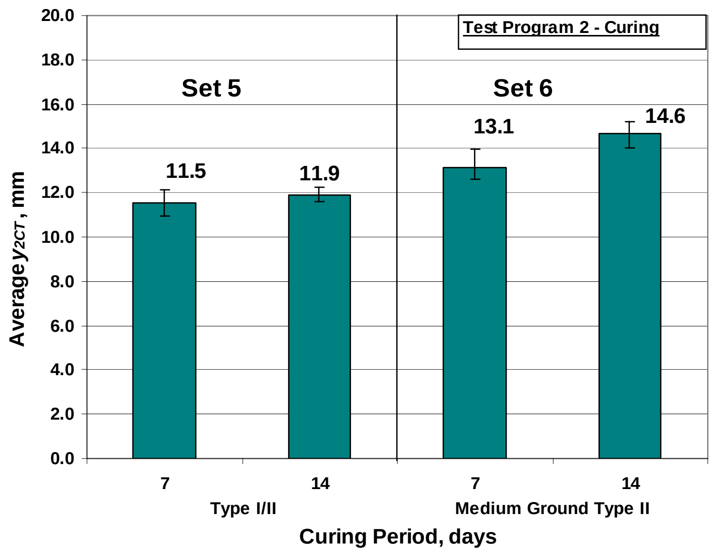


Fig. 3.26 Program 2 Sets 5 and 6 $\overline{y}_{2CT}$ versus Curing Period for concrete with 23.7% paste, a *w/c* ratio of 0.43, and 318 kg/m^3 (535 lb/yd^3) 100% portland cement. Set 5 concrete contains Type I/II cement. Set 6 concrete contains medium ground Type II cement.

Table 3.15 Student's t-Test Results for Program 2 Set 5

	Curing Period, days	D_{eff}	Curing Period, days		$\overline{y}_{2CT}$, mm	Curing Period, days	
			7	14		7	14
Curing Period	7	0.56		N	11.5		N
	14	0.52			11.9		

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

Table 3.16 Student's t-Test Results for Program 2 Set 6

	Curing Period, days	D_{eff}	Curing Period, days		$\overline{y}_{2CT}$, mm	Curing Period, days	
			7	14		7	14
Curing Period	7	0.82		Y 0.04 (96%)	13.1		Y 0.05 (95%)
	14	1.02			14.6		

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

3.10.5 Program 2 Sets 7 and 8 (24.4% paste, 0.45 *w/cm* ratio, and either 100% Type I/II or Medium Ground Type II Portland Cement)

The concrete in Program 2 set 7 includes Type I/II cement, while the concrete in set 8 includes medium ground Type II cement. For set 7 (concretes containing Type I/II cement), the Fick's profile (Fig. 3.27) for the concrete cured for 14 days is lower than the profile of the concrete cured for 7 days. The same is also apparent in the Fick's profile for the concrete containing medium ground Type II cement in set 8 (Fig. 3.28). These profiles suggest that longer curing decreases permeability and increases protection from chloride penetration because the chloride concentration is generally lower at all depths for the concrete cured for 14 days, than for 7 days.

For both sets, $\overline{y}_{2CT}$ for the concrete cured for 14 days is less than for the concrete cured for 7 days, indicating reduced permeability with the longer curing periods. The difference in $\overline{y}_{2CT}$ is greater for set 8, possibly indicating that concrete made with medium ground Type II cement may exhibit greater sensitivity to the curing period as compared to concrete made with the Type I/II cement.

The individual Fick's profiles and y_{2CT} for set 7 are provided in Figs. B.16 and B.17, and for set 8 in Figs. B.22 and B.23 in Appendix B.

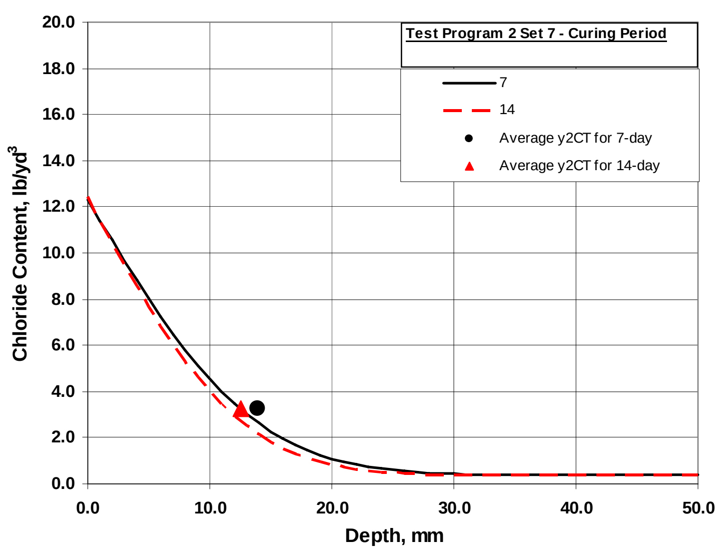


Fig. 3.27 Program 2 Set 7 Fick's profiles and $\overline{y}_{2CT}$ for concrete with Type I/II cement

The D_{eff} and $\overline{y}_{2CT}$ values for sets 7 and 8 are shown graphically in Figs. 3.29 and 3.30. The results for both performance measures indicate that increasing the curing period from 7 to 14 days decreases chloride penetration.

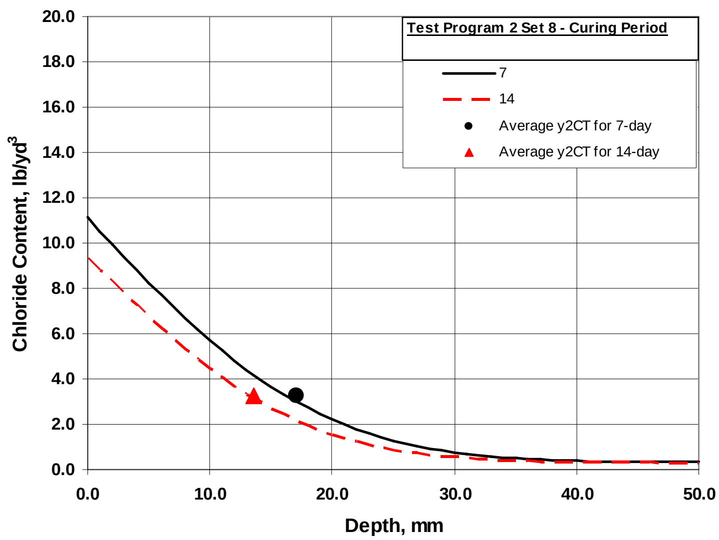


Fig. 3.28 Program 2 Set 8 Fick's profiles and $\overline{y}_{2CT}$ for concrete with Medium Ground Type II cement

For the concrete made with Type I/II cement (set 7) increasing the curing period from 7 to 14 days resulted in a decrease in the D_{eff} from 0.63 to 0.52 mm^2/day. For the concrete made with medium ground Type II cement (set 8), the increase in curing period resulted in a decrease in D_{eff} from 1.21 to 1.02 mm^2/day. Although the differences for both sets are not statistically significant (Tables 3.17 and 3.18), the trends are consistent and indicate that longer curing period result in decreased permeability.

The $\overline{y}_{2CT}$ decreased from 13.9 to 12.6 mm (0.55 to 0.50 in.) for set 7, and from 17.1 to 13.6 mm (0.67 to 0.54 in.) for set 8. The difference in $\overline{y}_{2CT}$ for set 7 is not statistically significant (Table 3.17), while the difference in $\overline{y}_{2CT}$ for set 8 is statistically significant at α = 0.06 (94%) (Table 3.18). The $\overline{y}_{2CT}$ results are in agreement and indicate that increased curing results in reduced chloride penetration.

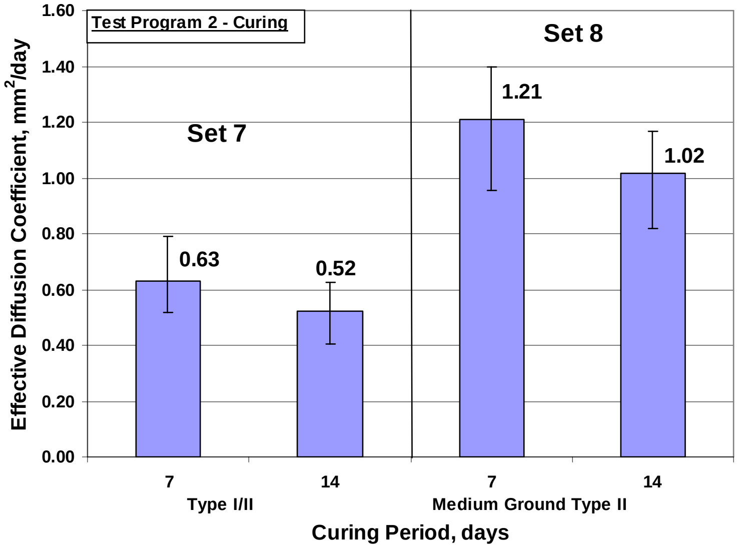


Fig. 3.29 Program 2 Sets 7 and 8 Effective Diffusion Coefficients versus Curing Period for concrete with 24.4% paste, a *w/c* ratio of 0.45, and 318 kg/m^3 (535 lb/yd^3) 100% portland cement. Set 7 concrete contains Type I/II cement. Set 8 concrete contains medium ground Type II cement.

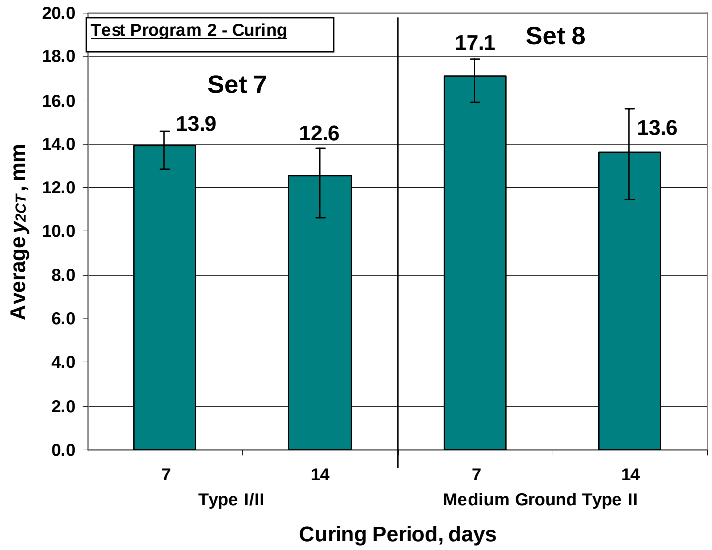


Fig. 3.30 Program 2 Sets 7 and 8 $\overline{y}_{2CT}$ versus Curing Period for concrete with 24.4% paste, a *w/c* ratio of 0.45, and 318 kg/m^3 (535 lb/yd^3) 100% portland cement. Set 7 concrete contains Type I/II cement. Set 8 concrete contains medium ground Type II cement.

Overall, D_{eff} and $\overline{y}_{2CT}$ results for sets 7 and 8 clearly indicate that increasing the curing period from 7 to 14 days decreases the permeability and enhances the concrete's resistance to chloride penetration.

Table 3.17 Student's t-Test Results for Program 2 Set 7

	Curing Period, days	D_{eff}	Curing Period, days		$\overline{y}_{2CT}$, mm	Curing Period, days	
			7	14		7	14
Curing Period	7	0.63		N	13.9		N
	14	0.52			12.6		

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

Table 3.18 Student's t-Test Results for Program 2 Set 8

	Curing Period, days	D_{eff}	Curing Period, days		$\overline{y}_{2CT}$, mm	Curing Period, days	
			7	14		7	14
Curing Period	7	1.21		N	17.1		Y 0.06 (94%)
	14	1.02			13.6		

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

3.10.6 Program 2 Summary

In general, the results of Program 2 indicate that longer curing reduces concrete permeability. For six of the eight sets, the D_{eff} results indicate that an increase in curing from 7 to 14 days helps and one of the two sets that do not indicate that additional curing helps was not statistically significant. The one set that included a 28-day curing period indicated a further reduction in D_{eff} with an increase in the curing period from 14 to 28 days. For five of the eight sets, the $\overline{y}_{2CT}$ results indicate that longer curing helps and two of the three sets that do not indicate that additional curing helps were not statistically significant. A brief discussion of the results follows.

Sets 1 and 7 include concrete with a *w/c* ratio of 0.45, similar paste contents (24.2% and 24.4%), and Type I/II cement. Although the values of D_{eff} and $\overline{y}_{2CT}$ for sets 1 and 7 cannot be directly compared because of differences in drying time between ponding and sampling (Section 3.7.1), it is appropriate to observe the general trends for these sets. Neither set produced differences in D_{eff} or $\overline{y}_{2CT}$ that were statistically significant. For Sets 1 and 7, Fick's profiles of the concretes cured for 7 and 14 days are similar and do not indicate significant differences in the permeability. In this program, the increase in curing from 7 to 14 days does not appear to significantly influence the permeability of the concrete made with Type I/II cement (sets 1 and 7) at a relatively low paste content (24.2% and 24.4%) and with a *w/c* ratio of 0.45.

The results for four sets (sets 1, 3, 5, and 7) with concrete containing Type I/II cement exhibit mixed results. Three of the four sets containing Type I/II cement did not exhibit statistically significant differences in D_{eff} or $\overline{y}_{2CT}$, making the results somewhat unclear. For two of the four sets, both performance measures indicate that increased curing decreases permeability, whereas one of the four sets has both performance measures indicate the opposite.

The four sets (sets 2, 4, 6, and 8) with concrete containing either coarse ground Type II cement or medium ground Type II cement exhibited greater sensitivity to and larger benefits from the longer curing period. The D_{eff} and $\overline{y}_{2CT}$ results for three of the four sets indicate decreased permeability with an increase in the curing period from 7 to 14 days, although not all of the differences are statistically significant. The set 6 results are in direct contrast to the trends, and have no explanation.

3.11 PROGRAM 3 – WATER-CEMENT RATIO

Program 3 includes five sets of concrete mixtures examining the effect of *w/c* ratio on the resistance to chloride penetration. All of the sets contain only portland cement. Each of the sets compares multiple *w/c* ratios for mixtures with paste contents of 24.4% or less and curing periods of 7 or 14 days. Additional Program 3 details are provided in Section 2.7.1. Mixture proportions, plastic concrete properties and compressive strengths are provided in Appendix A.

A summary of Program 3 is provided in Table 3.19. The concrete in sets 1 and 2 contain Type I/II cement and have curing periods of 7 and 14 days, respectively. Sets 3 and 4 are identical to sets 1 and 2 except they contain medium ground Type II cement.

The *w/c* ratio is recognized as a dominant factor affecting the overall permeability of concrete with increases in the *w/c* ratio resulting in an increase in permeability. It is not possible for concretes cast with a *w/c* ratio of 0.70 to achieve a discontinuous pore system, regardless of the length of wet curing (Mindess et al. 2003). Such concretes will thus always have high permeability, whereas concretes cast with a *w/c* ratio of 0.40 may achieve a discontinuous system of capillaries in as little as 3 days.

Table 3.19 Program 3 – Summary

Set	Cement Type	Cementitious Materials Content, kg/m^3 (lb/yd^3)	Curing Period, days	Paste Content, %	*w/c*
1	I/II	317 (535) 317 (535) 318 (535)	7	23.1 23.7 24.4	0.41 0.43 0.45
2	I/II	317 (535) 317 (535) 318 (535)	14	23.1 23.7 24.4	0.41 0.43 0.45
3	M.G. II	317 (535)	7	23.1 23.7 24.4	0.41 0.43 0.45
4	M.G. II	317 (535)	14	23.1 23.7 24.4	0.41 0.43 0.45
5	I/II	347 (583) 337 (566) 327 (550) 318 (535)	14	23.3	0.36 0.38 0.40 0.42

The construction practice having the most negative effect on concrete permeability is the practice of *retempering*, or adding water to the concrete just prior to placement to increase workability. Retempering increases the *w/c* ratio and is highly detrimental to the properties of the concrete, including the permeability. Retempering also increases shrinkage and reduces concrete strength. Retempering increases not only the water content and the *w/c* ratio, but also the paste content of the mixture. The first four sets of this program study the combined effects of changing the *w/c* ratio and paste content, similar to the practice of retempering.

The first four sets in this program study the effects of retempering on LC-HPC. For each of these sets, the *w/c* ratio (and subsequent paste and water contents) is varied from 0.41 to 0.45. The concrete mixtures in these sets contain 317 kg/m^3 (535 lb/yd^3) of cement. Changes in the *w/c* ratio from 0.41 to 0.45 for this cement content represent a change in the water content from 130 kg/m^3 (219 lb/yd^3) to 143 kg/m^3 (241 lb/yd^3), a difference of 13 kg/m^3 (22 lb/yd^3). The corresponding change in paste content due to this change in *w/c* ratio (and water content) is from 23.1% to 24.4% paste. Similar programs studying the effect of *w/c* ratio on free shrinkage are described in the companion report by Lindquist et al. (2008).

The type of cement and the curing period are also varied in Program 3. Sets 1 and 2 contain Type I/II cement and are cured for 7 and 14 days respectively. Sets 3 and 4 contain medium ground Type II cement and are also cured for 7 and 14 days respectively. Because both cement type and curing period affect permeability, it is expected that this would be apparent in the results.

Concrete made with medium ground cement may have larger diameter pores and should, therefore, have greater permeability than cement manufactured with a normal (fine) grind. It is expected that sets 3 and 4 should have higher permeability than sets 1 and 2, and that each set cured for 14 days should have lower permeability than its corresponding set cured for 7 days. As shown in Program 1, increased paste content generally has the effect of decreasing permeability. Therefore, the results of sets 1 though 4 examine the overall effect of competing parameters on permeability by both increasing the paste content (which decreases permeability) and increasing the *w/c* ratio (which increases permeability).

The effect of *w/c* ratio alone on the permeability of concrete is investigated in set 5 by varying the *w/c* ratio from 0.36 to 0.42 while maintaining a constant paste content of 23.3%. This is accomplished by adjusting the cement content and the water content to achieve the desired *w/c* ratio while maintaining the same volume of paste. In this way, the effect of the *w/c* ratio is isolated from the effect of the paste content which is separately investigated in Program 1.

The results of Program 3 are in general agreement with the expectations. The results indicate that increasing the *w/c* ratio, either in combination with increased paste content or while holding the paste content constant increases the permeability and the chloride penetration into concrete. This behavior was most pronounced in the concrete made with medium ground Type II cement.

3.11.1 Program 3 Set 1 (535 lb/yd^3 Type I/II cement, 7-day curing)

For the concrete in Program 3 set 1, the Fick's profiles and $\overline{y}_{2CT}$ are shown in Fig. 3.31. The profile for the concrete with a *w/c* ratio of 0.43 is lower than the profiles for the concretes with *w/c* ratios of 0.41 and 0.45. This would suggest that the concrete with the 0.43 *w/c* ratio has the lowest permeability. It is unclear why this is the case. $\overline{y}_{2CT}$ for the 0.43 *w/c* ratio mixture is lower than the other two, following the same trend as the profiles. The individual chloride profiles and the y_{2CT} for the three concrete batches in set 1 are presented in Figs. B.12, B.14 and B.16 in Appendix B.

The D_{eff} and $\overline{y}_{2CT}$ for set 1 are presented graphically in Figs. 3.32 and 3.33.

The D_{eff} and $\overline{y}_{2CT}$ results for the concretes in set 1 follow the same trends as the Fick's profiles. The D_{eff} values are 0.72, 0.56 and 0.63 mm^2/day (Fig. 3.32), with the 0.43 *w/c* ratio concrete having the lowest value. The $\overline{y}_{2CT}$ values follow the same trend (Fig. 3.33). The differences in the performance measures for the 0.43 *w/c* ratio concrete are statistically significant (Table 3.20), with the exception of the D_{eff} difference between the concretes with the 0.45 *w/c* ratio. This pattern could be explained by an error during batching of either the 0.41 or the 0.43 *w/c* ratio mixture. Because this pattern is consistent but unexplained, it is helpful to consider the trend

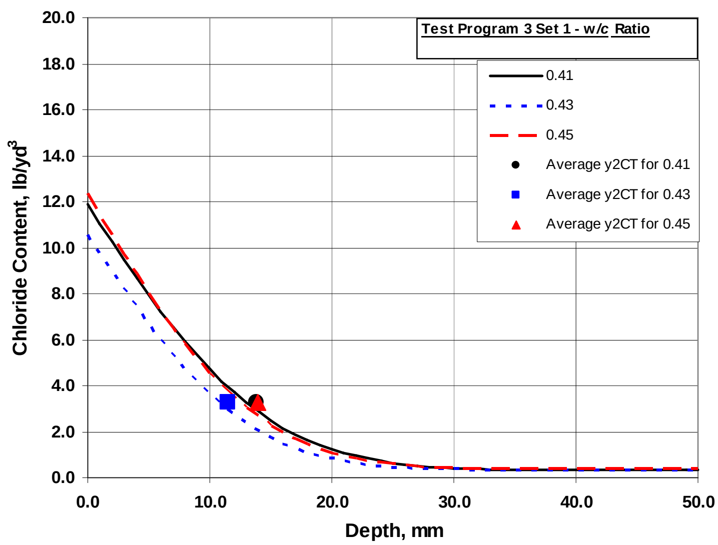


Fig. 3.31 Program 3 Set 1 Fick's profiles and $\overline{y}_{2CT}$ for concrete with *w/c* ratios of 0.41, 0.43, and 0.45

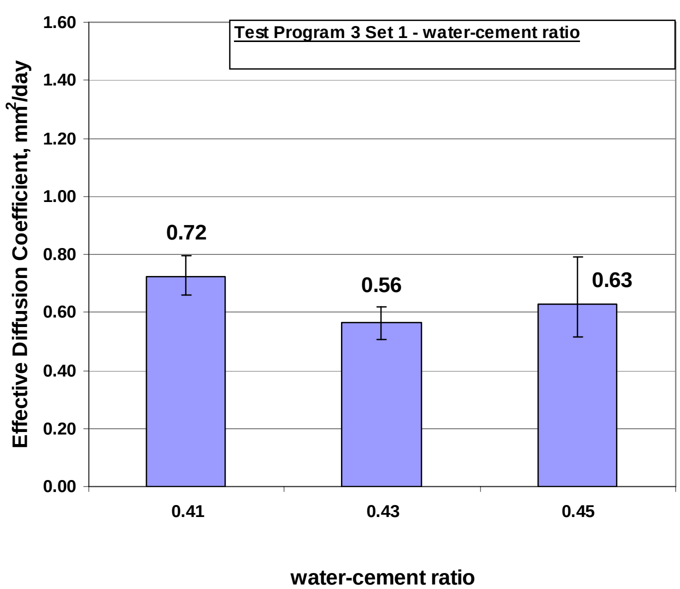


Fig. 3.32 Program 3 Set 1 Effective Diffusion Coefficients versus Water-Cement Ratio for concrete with 318 kg/m^3 (535 lb/yd^3) Type I/II cement and 7 days curing

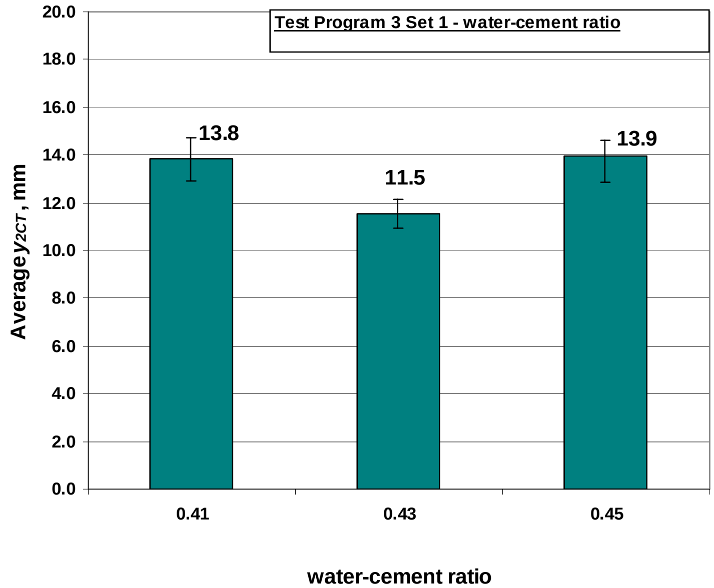


Fig. 3.33 Program 3 Set 1 $\bar{y}_{2CT}$ versus Water-Cement Ratio for concrete with 318 kg/m^3 (535 lb/yd^3) Type I/II cement and 7 days curing

between the 0.41 and 0.45 *w/c* ratio concretes, for which there is no statistical difference in either the D_{eff} or $\bar{y}_{2CT}$ results (Table 3.20). This would suggest that for mixtures containing relatively low paste contents, Type I/II cement and cured for 7 days, the addition of water necessary to change the *w/c* ratio from 0.41 to 0.45 [a change in water content of 13 kg/m^3 (22 lb/yd^3)] has no significant effect on the permeability.

For this set, the combined influence of *w/c* ratio and paste content did not have a large effect on the permeability.

Table 3.20 Student's t-Test Results for Program 3 Set 1

	Curing Period, days	D_{eff}	*w/c*			$\bar{y}_{2CT}$, mm	*w/c*		
			0.41	0.43	0.45		0.41	0.43	0.45
w/c	0.41	0.71		Y 0.10 (90%)	N	13.8		Y 0.07 (93%)	N
	0.43	0.56			N	11.5			Y 0.07 (93%)
	0.45	0.63				13.9			

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

3.11.2 Program 3 Set 2 (535 lb/yd^3 Type I/II cement, 14-day cure)

The Fick's profiles and $\overline{y}_{2CT}$ values for the concretes in Program 3 set 2 are nearly identical, as shown in Fig. 3.34, indicating little difference in permeability. The individual chloride profiles and the y_{2CT} for the three concrete batches in set 2 are presented in Figs. B.13, B.15 and B.17 in Appendix B.

The D_{eff} and $\overline{y}_{2CT}$ results for set 2 are presented graphically in Figs. 3.35 and 3.36. As shown in Table 3.21, the differences in values are not statistically significant, an observation that is consistent with the results in set 1.

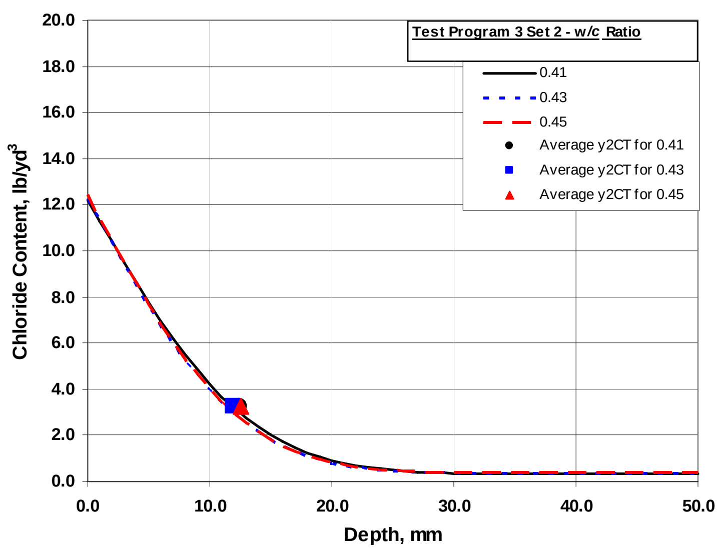


Fig. 3.34 Program 3 Set 2 Fick's profiles and $\overline{y}_{2CT}$ for concrete with *w/c* ratios of 0.41, 0.43, and 0.45

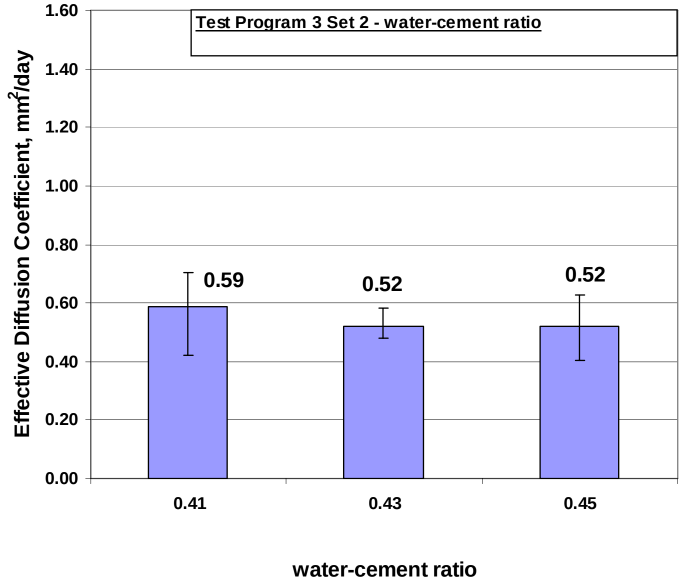


Fig. 3.35 Program 3 Set 2 Effective Diffusion Coefficients verus Water-Cement Ratio for concrete with 318 kg/m^3 (535 lb/yd^3) Type I/II cement and 14 days curing

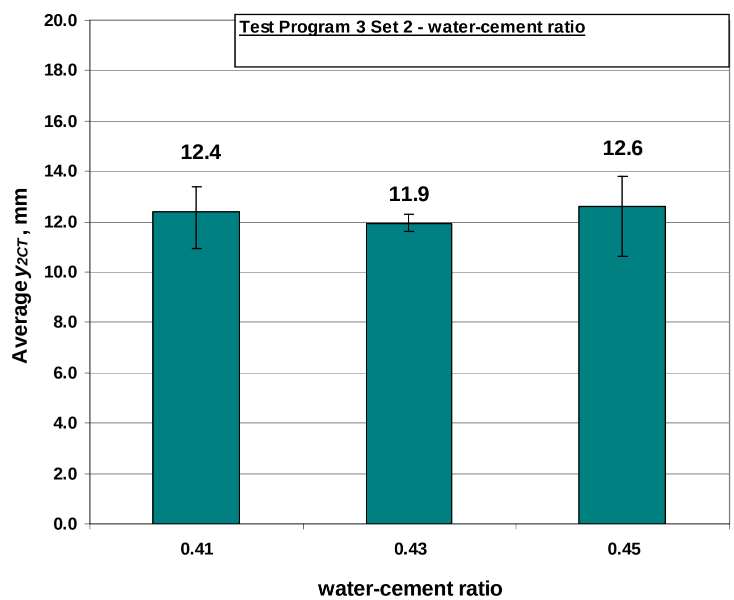


Fig. 3.36 Program 3 Set 2 $\overline{y}_{2CT}$ versus Water-Cement Ratio for concrete with 318 kg/m^3 (535 lb/yd^3) Type I/II cement and 14 days curing

Table 3.21 Student's t-Test Results for Program 3 Set 2

	Curing Period, days	D_{eff}	*w/c*			$\overline{y}_{2CT}$, mm	*w/c*		
			0.41	**0.43**	**0.45**		**0.41**	**0.43**	**0.45**
w/c	**0.41**	0.59		N	N	12.4		N	N
	0.43	0.52			N	11.9			N
	0.45	0.52				12.6			

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

3.11.3 Program 3 Set 3 (535 lb/yd^3 medium ground Type II cement, 7-day cure)

The concrete in sets 3 and 4 differ from that in sets 1 and 2 with medium ground Type II cement used in place of Type I/II cement. As discussed previously in Section 3.11, the use of medium ground cement should result in higher permeability for sets 3 and 4 as compared to sets 1 and 2.

For set 3, the Fick's profile and $\overline{y}_{2CT}$ value for the concrete with a *w/c* ratio of 0.45 (Fig. 3.37) lies clearly above the profiles and values of the concrete with *w/c* ratios of 0.41 and 0.43, indicating that the 0.45 *w/c* ratio mixture has greater permeability than the 0.41 and 0.43 *w/c* ratio mixtures. The profile and value of the 0.41 *w/c* ratio mixture lies between the profile and values of the 0.43 and 0.45 *w/c* ratio mixtures. The individual chloride profiles and y_{2CT} for the concrete batches in set 3 are presented in Figs. B.18, B.20 and B.22 in Appendix B.

The D_{eff} and $\overline{y}_{2CT}$ for set 3 are presented graphically in Figs. 3.38 and 3.39.

The D_{eff} values in Fig. 3.38 increase considerably, from 0.88 to 1.21 mm^2/day, with an increase in *w/c* ratio from 0.41 to 0.45. The range bars for the 0.41 and 0.45 *w/c* ratio mixtures show the significant scatter, particularly for the 0.41 *w/c* ratio specimens. Due to the scatter, the results are not statistically significant (Table 3.22). The only statistically significant difference is between D_{eff} values for *w/c* ratios of 0.43 and 0.45 (23.7% and 24.4% paste) with D_{eff} changing from 0.82 to 1.21 mm^2/day, indicating increased permeability with increasing *w/c* ratio (and paste). The $\overline{y}_{2CT}$ results generally agree with the D_{eff} results, although scatter is apparent in

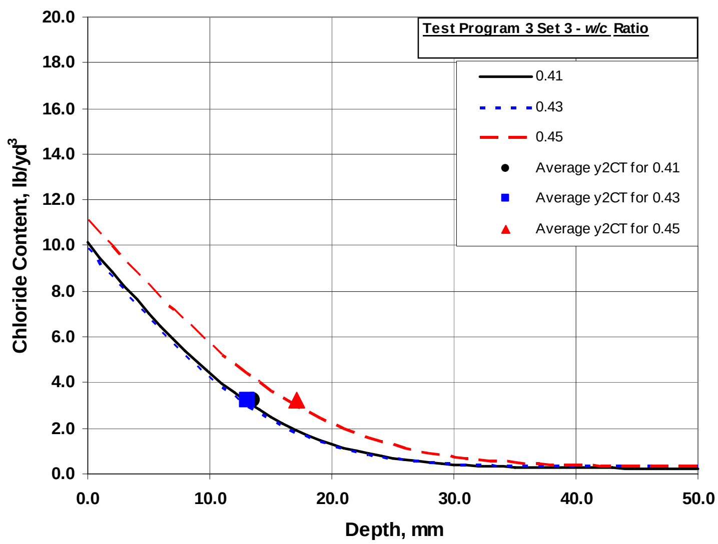


Fig. 3.37 Program 3 Set 3 Fick's profiles and $\overline{y}_{2CT}$ for concrete with *w/c* ratios of 0.41, 0.43, and 0.45

the results for the 0.41 *w/c* ratio specimens. Increases in the *w/c* ratio from 0.41 to 0.45 resulted in increases in $\overline{y}_{2CT}$ from 13.5 to 17.1 mm (0.53 to 0.67 in.) and are statistically significant (Table 3.22). Even more clear is the increase in the *w/c* ratio from 0.43 to 0.45 resulting in an increase in $\overline{y}_{2CT}$ from 13.1 to 17.1 mm (0.52 to 0.67 in.), statistically significant at significance level of $\alpha < 0.01$ (greater than 99%) (Table 3.33). The D_{eff} and $\overline{y}_{2CT}$ results for this set generally indicate increasing permeability with increasing *w/c* ratio; however, significant scatter makes the significance of the results unclear.

Overall, even with the scatter, the concrete mixtures containing medium ground Type II cement and cured for 7 days, exhibited an increase in permeability and chloride penetration with increases in the *w/c* ratio and paste content due to addition of water alone.

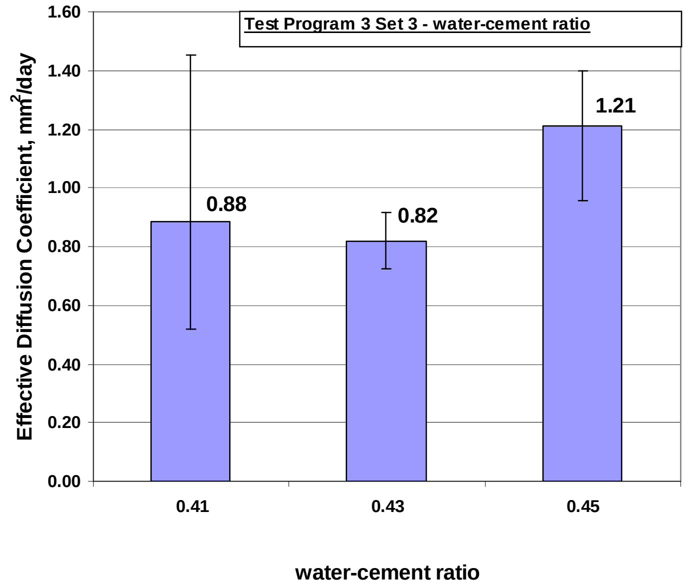


Fig. 3.38 Program 3 Set 3 Effective Diffusion Coefficients versus Water-Cement Ratio for concrete with 318 kg/m^3 (535 lb/yd^3) medium ground Type II cement and 7 days curing

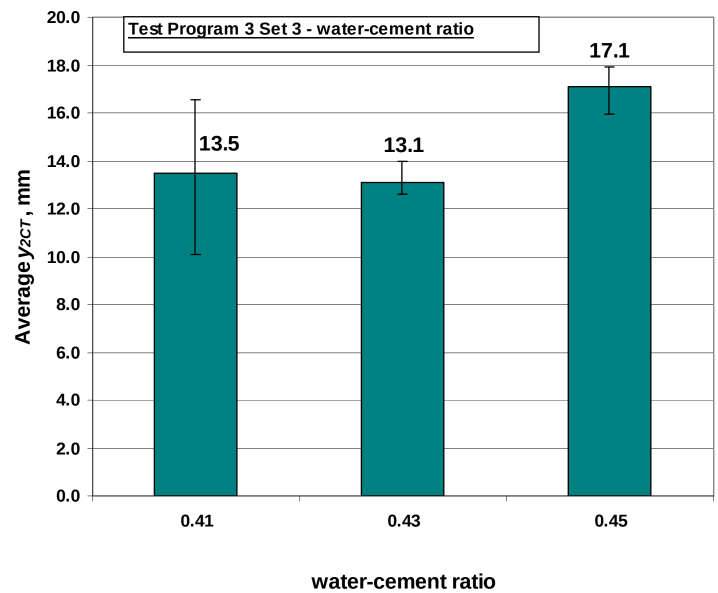


Fig. 3.39 Program 3 Set 3 $\overline{y}_{2CT}$ versus Water-Cement Ratio for concrete with 318 kg/m^3 (535 lb/yd^3) medium ground Type II cement and 7 days curing

Table 3.22 Student's t-Test Results for Program 3 Set 3

	Curing Period, days	D_{eff}	*w/c*			$\overline{y}_{2CT}$, mm	*w/c*		
			0.41	**0.43**	**0.45**		**0.41**	**0.43**	**0.45**
w/c	**0.41**	0.88		N	N	13.5		N	Y 0.14 (86%)
	0.43	0.82			Y 0.06 (94%)	13.1			Y 0.01 (99%)
	0.45	1.21				17.1			

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

3.11.4 Program 3 Set 4 (535 lb/yd^3 medium ground Type II cement, 14-day cure)

For the concrete in Program 3 set 4, the Fick's profile and $\overline{y}_{2CT}$ value for the concrete with 0.41 *w/c* ratio is below those of the 0.43 and 0.45 *w/c* ratio mixtures (Fig. 3.40), suggesting that the concrete with the lowest *w/c* ratio is the least permeable. Fick's profile and $\overline{y}_{2CT}$ value for the 0.45 *w/c* ratio mixture are slightly below those for the 0.43 *w/c* ratio mixture, but the profiles are similar. The individual chloride profiles and the y_{2CT} depths for the concrete batches in set 4 are presented in Figs. B.19, B.21 and B.23 in Appendix B.

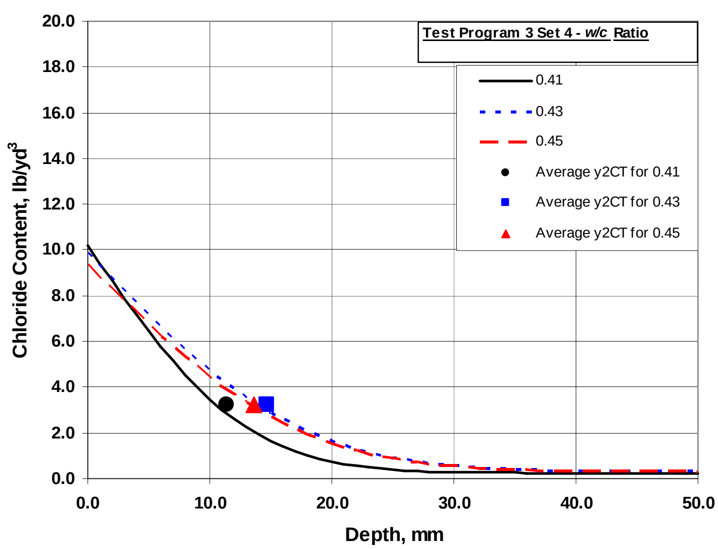


Fig. 3.40 Program 3 Set 4 Fick's profiles and $\overline{y}_{2CT}$ for concrete with *w/c* ratios of 0.41, 0.43, and 0.45

The D_{eff} and $\overline{y}_{2CT}$ for set 4 are presented graphically in Figs. 3.41 and 3.42.

The D_{eff} for the 0.41 *w/c* ratio mixture is 0.56 mm^2/day and is clearly lower than the D_{eff} value for the other two mixtures, 1.02 mm^2/day. The differences in D_{eff} are statistically significant between the 0.41 *w/c* ratio mix and the other two mixtures at significance levels of $\alpha = 0.03$ (97%) and $\alpha = 0.08$ (92%) (Table 3.23).

The results for the $\overline{y}_{2CT}$ are in general agreement with the D_{eff} results, indicating an increase in chloride penetration with increasing *w/c* ratio. An increase in the *w/c* ratio from 0.41 to 0.45 resulted in an increase in $\overline{y}_{2CT}$ from 11.4 to 13.6 mm (0.45 to 0.54 in.), but the difference is not statistically significant (Table 3.23) due to the scatter in the $\overline{y}_{2CT}$ results for the 0.45 *w/c* ratio mixture.

The D_{eff} and $\overline{y}_{2CT}$ results of both parameters for set 4 generally indicate that increases in the *w/c* ratio (and paste content) result in increases in permeability and chloride penetration.

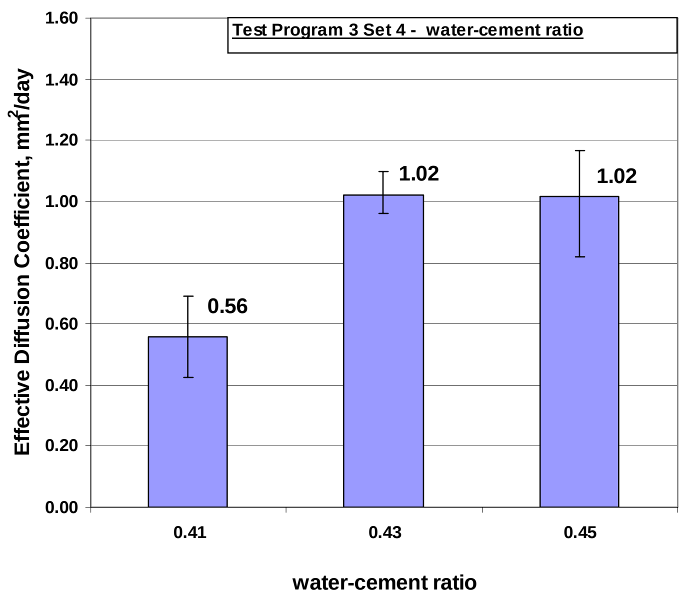


Fig. 3.41 Program 3 Set 4 Effective Diffusion Coefficients versus Water-Cement Ratio for concrete with 318 kg/m^3 (535 lb/yd^3) medium ground Type II cement and 14 days curing

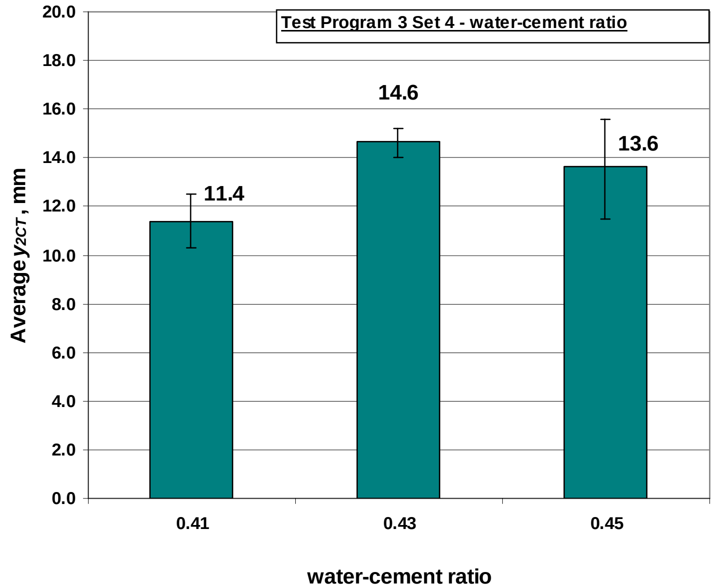


Fig. 3.42 Program 3 Set 4 $\overline{y}_{2CT}$ versus Water-Cement Ratio for concrete with 318 kg/m^3 (535 lb/yd^3) medium ground Type II cement and 14 days curing

Table 3.23 Student's t-Test Results for Program 3 Set 4

	Curing Period, days	D_{eff}	***w/c*** 0.41	***w/c*** 0.43	***w/c*** 0.45	$\overline{y}_{2CT}$, mm	***w/c*** 0.41	***w/c*** 0.43	***w/c*** 0.45
w/c	**0.41**	0.56		Y 0.03 (97%)	Y 0.08 (92%)	11.4		Y 0.05 (95%)	N
	0.43	1.02			N	14.6			N
	0.45	1.02				13.6			

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

3.11.5 Program 3 Set 5 (23.3% paste, Type I/II cement, 14-day cure)

Of the four concrete mixtures in Program 3 set 5, the Fick's profile and $\overline{y}_{2CT}$ values for the two with the lowest *w/c* ratio (0.36 and 0.38) are nearly identical and lie below those for the 0.40 and 0.42 *w/c* ratio mixtures, as shown in Fig. 3.43, indicating that the mixtures with the lowest *w/c* ratios have lower permeability. The surface concentrations for three of the mixtures are approximately the same at about 8.3 kg/m^3 (14 lb/yd^3). The surface concentration of the 0.42 *w/c* ratio mixture is about

9.5 kg/m^3 (16 lb/yd^3). The individual chloride profiles and y_{2CT} for the four concrete batches in set 5 are presented in Figs. B.25, B.26, B.27 and B.28 in Appendix B.

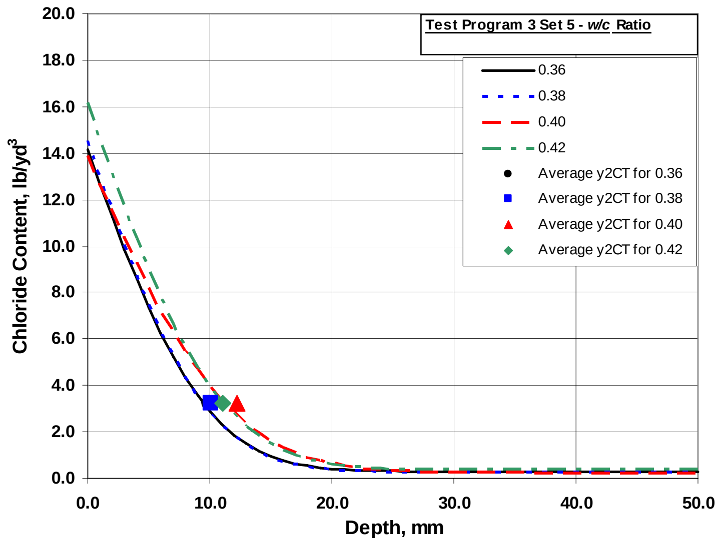


Fig. 3.43 Program 3 Set 5 Fick's profiles and $\overline{y}_{2CT}$ for concrete with *w/c* ratios of 0.36, 0.38, 0.40 and 0.42

The D_{eff} and $\overline{y}_{2CT}$ for set 5 are presented graphically in Figs. 3.44 and 3.45.

Set 5 is used to study the effect of *w/c* ratio alone on the permeability of concrete by separating it from the paste content. The paste content for mixtures in this set is constant. The results indicate a slight but generally increasing trend in the D_{eff} with increasing *w/c* ratio from 0.36 to 0.42 (Fig. 3.44). The D_{eff} for the 0.40 and 0.42 *w/c* ratio mixtures are higher than for the 0.36 and 0.38 *w/c* ratio mixtures, with the 0.40 *w/c* ratio mixture having the greatest D_{eff}. The differences (Table 3.24a) in D_{eff} are significant for *w/c* ratios of 0.36 and 0.40, and for 0.38 and 0.40 at $\alpha = 0.03$ (97%) and $\alpha = 0.05$ (95%) respectively.

The same trend is also seen in Fig. 3.45 for the $\overline{y}_{2CT}$ values. $\overline{y}_{2CT}$ generally increases with increasing *w/c* ratio indicating increased chloride penetration. The $\overline{y}_{2CT}$ values for mixtures with *w/c* ratio of 0.36 and 0.42 are 10.0 to 11.1 mm (0.39 to 0.44 in.), representing a statistically significant difference (Table 3.24b) at $\alpha = 0.02$ (98%). The differences between all the $\overline{y}_{2CT}$ results are statistically significant, except for the 0.36 and 0.38 *w/c* ratio mixtures. The decrease in $\overline{y}_{2CT}$ with increase in *w/c* ratio from

0.40 to 0.42 does not follow the expected trend; however, the level of significance for this difference is also lower, at α = 0.18 (82%).

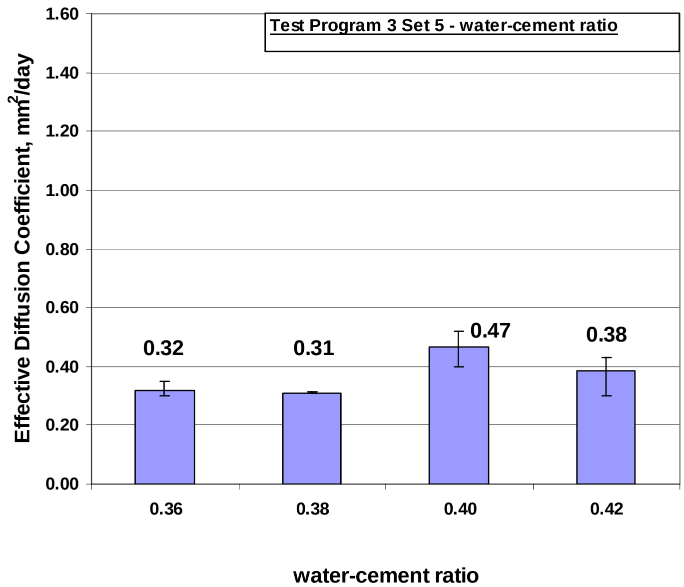


Fig. 3.44 Program 3 Set 5 Effective Diffusion Coefficients versus Water-Cement Ratio for concrete with 23.3% paste, Type I/II cement and 14 days curing

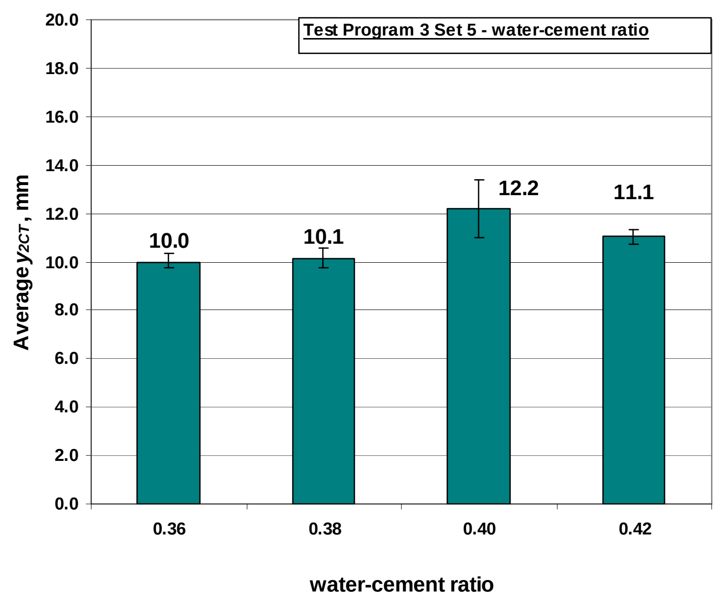


Fig. 3.45 Program 3 Set 5 $\overline{y}_{2CT}$ versus Water-Cement Ratio for concrete with 23.3% paste, Type I/II cement and 14 days curing

An increase in *w/c* ratio from 0.36 to 0.42 is a relatively mild change, but differences in permeability and chloride penetration are still observed. Overall, set 5 results show an increase in permeability and chloride penetration with an increase in *w/c* ratio.

Table 3.24 Student's t-Test Results for Program 3 Set 5

(a) D_{eff}

	w/c	**D_{eff}**	***w/c* Ratio**			
			0.36	**0.38**	**0.40**	**0.42**
***w/c* Ratio**	**0.36**	0.32		N	Y 0.03 (97%)	N
	0.38	0.31			Y 0.05 (95%)	N
	0.40	0.47				N
	0.42	0.38				

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

(b) $\overline{y}_{2CT}$

	w/c	**$\overline{y}_{2CT}$, mm**	***w/c* Ratio**			
			0.36	**0.38**	**0.40**	**0.42**
***w/c* Ratio**	**0.36**	10.0		N	Y 0.04 (96%)	Y 0.02 (98%)
	0.38	10.1			Y 0.12 (88%)	Y 0.09 (91%)
	0.40	12.2				Y 0.18 (82%)
	0.42	11.1				

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

3.11.6 Program 3 - Comparisons Between Sets 1 Through 4

The mean values of D_{eff} and $\overline{y}_{2CT}$ were determined for each set as a general indicator of overall set performance for the purpose of comparing between sets. Each of the sets (1 through 4) had mixtures with the same *w/c* ratios and paste contents. The mean values of these performance measures provide a way to determine the effect of cement type and curing time on the overall performance of the concrete in the set. Mean values of D_{eff} and $\overline{y}_{2CT}$ for sets 1 through 4 are presented in Table 3.25 and shown graphically in Fig. 3.46.

Table 3.25 Program 3 Mean values of D_{eff} and $\overline{y}_{2CT}$ for sets 1 through 4

Set	Mean D_{eff}, mm^2/day	Mean $\overline{y}_{2CT}$, mm, mm
1	0.64	13.1
2	0.54	12.3
3	0.97	14.6
4	0.87	13.2

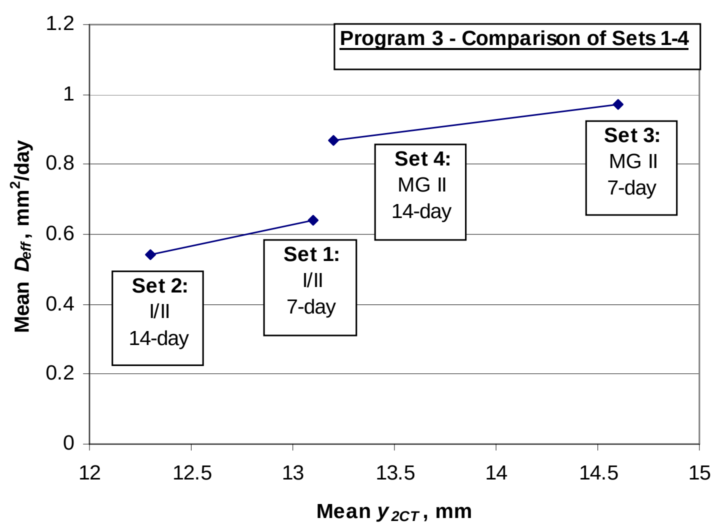


Fig. 3.46 Program 3 Mean values of D_{eff} versus $\overline{y}_{2CT}$ for sets 1 through 4

The lines connecting data points in Fig. 3.46 indicate companion sets cast from the same concrete batch but cured for different lengths of time. For each of the companion sets, the 14-day curing period resulted in lower permeability (mean D_{eff}) and lower chloride penetration (mean $\overline{y}_{2CT}$) than provided by 7 days of curing. The relative performance of concretes cast with difference types of cement is also apparent. The sets cast with medium ground Type II cement exhibit greater permeability (higher mean D_{eff}) and increased chloride penetration (higher mean $\overline{y}_{2CT}$) than the corresponding sets cast with Type I/II cement.

In summary, extending the curing period from 7 to 14 days improves the protection from chloride penetration. These results are in agreement with the results of Program 2, where the effect of curing period was also examined. The concrete cast with Type I/II cement exhibits lower permeability than concrete cast with medium ground Type II cement. These results are in agreement with the results of Program 4, where the effect of cement type is further examined.

3.11.7 Program 3 Summary

Program 3 considers the effect of *w/c* ratio on the permeability of concrete and its ability to resist chloride penetration. The first four sets consider the combined effect of *w/c* ratio and paste content. For these sets, the *w/c* ratio and paste content are both changed (increased) by the addition of water to the mix, similar to the field practice of *retempering*. Concrete mixtures in sets 1 and 2, made with Type I/II cement, exhibit no significant difference in their permeability characteristics due to increases in the *w/c* ratio from 0.41 to 0.45 and the paste content from 23.1% to 24.4%. Concrete mixtures in sets 3 and 4, made with medium ground Type II cement, exhibit increases in permeability and chloride penetration with increases in the *w/c* ratio from 0.41 to 0.45 and the paste content from 23.1% to 24.4%. In this program, the concretes cured for 14 days performed better than concretes cured for 7 days, and concretes cast with Type I/II cement performed better than concretes cast with medium ground Type II cement. Considering the effect of *w/c* ratio alone, set 5 results indicate slight increases in permeability with increases in the *w/c* ratio from 0.36 to 0.42.

3.12 PROGRAM 4 – CEMENT TYPE

Program 4 includes eight sets of concrete mixtures examining the effect of cement type on the resistance to chloride penetration. Each set compares two types of cement for concrete with the same *w/c* ratio, cement content, paste content and curing period. All of the mixtures in this program contain 318 kg/m^3 (535 lb/yd^3) of cement. The *w/c* ratios for different sets range from 0.41 to 0.45, and the corresponding paste contents range from 23.1% to 24.2%. Additional Program 4 details are provided in Section 2.7.1. Mixture proportions, plastic concrete properties and compressive strengths are provided in Appendix A.

The concrete in this program contains two types of cement, Type I/II and Type II, obtained from multiple samples. Three samples of Type I/II cement are used with Blaine finenesses ranging from 3674 to 3816 cm^3/g. Typical Blaine fineness values for standard Type I cements used today are in the range of 3500–4000 cm^3/g. The Type I/II cement samples used in this program fall within this range. Two samples of Type II are used in Program 4, with Blaine finenesses of 3060 and 3351 cm^3/g. Blaine fineness values for coarse ground cement can be in the range of 2800–3200 cm^3/g. One sample of Type II cement (Blaine of 3060 cm^3/g) used in this program falls within this range and is, therefore, termed "coarse ground Type II" in this discussion. The other Type II cement sample (Blaine of 3351 cm^3/g) falls above the range for coarse ground cement and below the range for standard Type I cements. It is, therefore, termed "medium ground Type II" in this discussion. The coarseness of the grind affects overall rate of hydration and the diameter of the capillary pores in concrete. Concrete made with a coarse ground cement should have larger diameter capillary pores and be generally more permeable than concretes made with a more finely ground cement. The results of this study generally agree with this theory; in six of the eight sets in Program 4, the concretes made with the coarse and medium ground cement concrete have higher permeabilities than those cast with Type I/II cement (finely ground).

The tricalcium silicate C_3S (Alite) values for the Type II cements used in this Program are 62 and 65 percent, somewhat higher than the Type I/II cements, which have values of 50, 53, and 52 percent. The dicalcium silicate C_2S (Belite) values for the Type II cements are 11 and 13 percent, somewhat lower than the Type I/II cements, which have values of 23, 21, and 22 percent. More detailed information about the properties and chemical composition of the cements used in this study are found in Chapter 2 Section 2.2.1.

Sets 1 and 2 compare the performance of concretes made with Type I/II and coarse ground Type II cement. Sets 3 through 8 compare the performance of concrete made with Type I/II and the medium ground Type II cement. Three of the companion sets (3 and 4, 5 and 6, and 7 and 8) were cast from the same batches of concrete but differed in length of curing. Sets 1 and 2 were cast in separate batches. A summary of Program 4 is provided in Table 3.39.

Table 3.26 Program 4 – Summary

Set	Paste Content, %	*w/c*	Curing Period, days	Cement Type
1	24.2	0.45	7	I/II-a I/II-b CG[1] II-a CG[1] II-b
2	24.2	0.45	14	I/II CG[1] II
3	24.4	0.45	7	I/II MG[2] II
4	24.4	0.45	14	I/II MG[2] II
5	23.7	0.43	7	I/II MG[2] II
6	23.7	0.43	14	I/II MG[2] II
7	23.1	0.41	7	I/II MG[2] II
8	23.1	0.41	14	I/II MG[2] II

[1] "CG" denotes coarse ground as discussed in Section 3.12.
[2] "MG" denotes coarse ground as discussed in Section 3.12.

3.12.1 Program 4 Sets 1 and 2 (24.2% paste, 0.45 *w/c* ratio, and either Type I/II or Coarse Ground Type II Portland Cement)

For the concrete in set 1 (7-day cure), the Fick's profiles for the concretes containing Type I/II cement drop below the profile of the concretes containing the coarse ground Type II cement at about 8 mm (0.31 in.) and remain below for all lower depths, as shown in Fig. 3.47. The "a" and "b" designation indicate two separate batches with identical mix designs. The lower chloride concentrations at these depths indicate lower permeability at the deeper levels. The values of $\overline{y}_{2CT}$ for the concretes containing Type I/II cement are slightly smaller than for the concrete containing the coarse ground Type II cement, also indicating better protection from chloride penetration. The individual chloride profiles and y_{2CT} for the concrete batches in set 1 are presented in Figs. B.5, B.9, B.3 and B.4, and for set 2 in Figs. B.8 and B.10 in Appendix B.

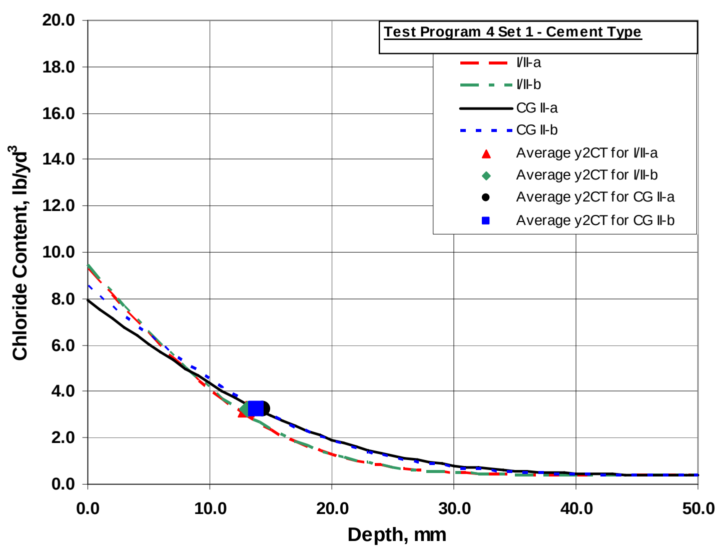


Fig. 3.47 Program 4 Set 1 Fick's profiles and $\overline{y}_{2CT}$ for concrete with Types I/II and coarse ground Type II cement, cured for 7-days

For the concrete in set 2 (14-day cure), the Fick's profiles for the concretes containing Type I/II cement and coarse ground Type II cement are nearly identical, as shown in Fig. 3.48, indicating similar permeabilities. The $\overline{y}_{2CT}$ for the two concretes are also similar, although the $\overline{y}_{2CT}$ for the concrete containing coarse ground Type II cement is slightly lower.

The individual chloride profiles and the y_{2CT} depths for the concrete batches in set 1 are presented in Figs. B.5, B.9, B.3 and B.4, and for set 2 in Figs. B.8 and B.10 in Appendix B.

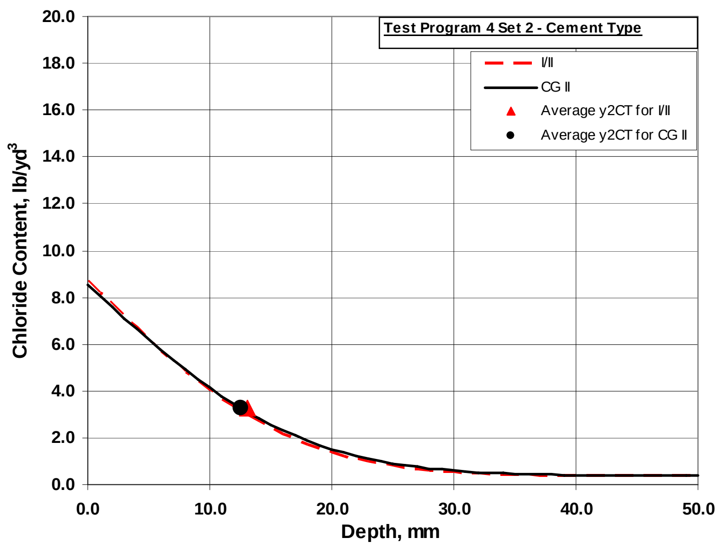


Fig. 3.48 Program 4 Set 2 Fick's profiles and $\overline{y}_{2CT}$ for concrete with Types I/II and coarse ground Type II cement, cured for 14 days

The D_{eff} and $\overline{y}_{2CT}$ for sets 1 and 2 are presented graphically in Figs. 3.49 and 3.50.

For set 1 (7-day cure), the concrete made with Type I/II cement has distinctly lower D_{eff} values (0.84 and 0.84 mm^2/day) than the concrete made with coarse ground Type II cement (1.35 and 1.26 mm^2/day) (Fig. 3.49). The D_{eff} values for the concrete containing coarse ground Type II cement are the highest in the study. The large difference in the D_{eff} values for the two cement types represents a statistically significant difference (Table 3.27a). The $\overline{y}_{2CT}$ values for set 1 follow the same trend, although not as dramatically so, with values of 13.0 and 13.1 mm (0.51 and 0.52 in.) for concrete made with Type I/II cement and 14.4 and 13.8 mm (0.57 and 0.54 in.) for the concrete made with coarse ground Type II cement (Fig. 3.50). The differences between the $\overline{y}_{2CT}$ values for the Type I/II specimens and the coarse ground Type II

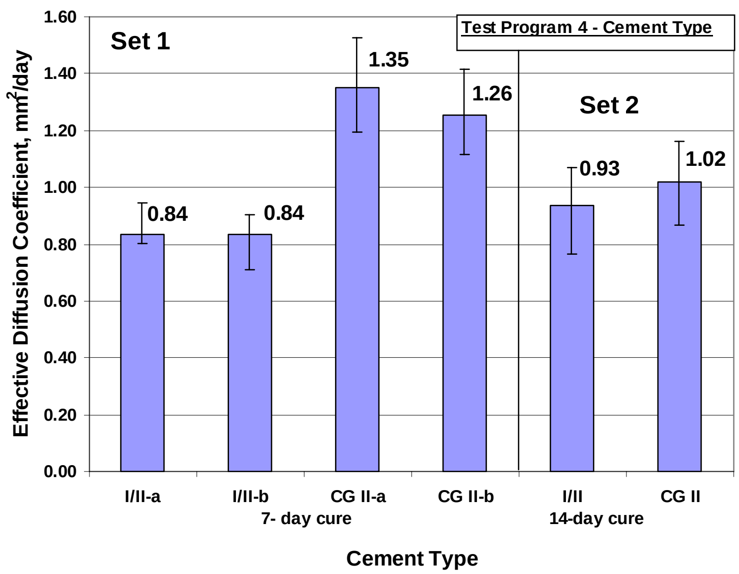


Fig. 3.49 Program 4 Sets 1 and 2 Effective Diffusion Coefficients versus Cement Type for concrete with 24.2% paste, a *w/c* ratio of 0.45 and 318 kg/m^3 (535 lb/yd^3) portland cement. Set 1 concrete was cured for 7 days. Set 2 concrete was cured for 14 days.

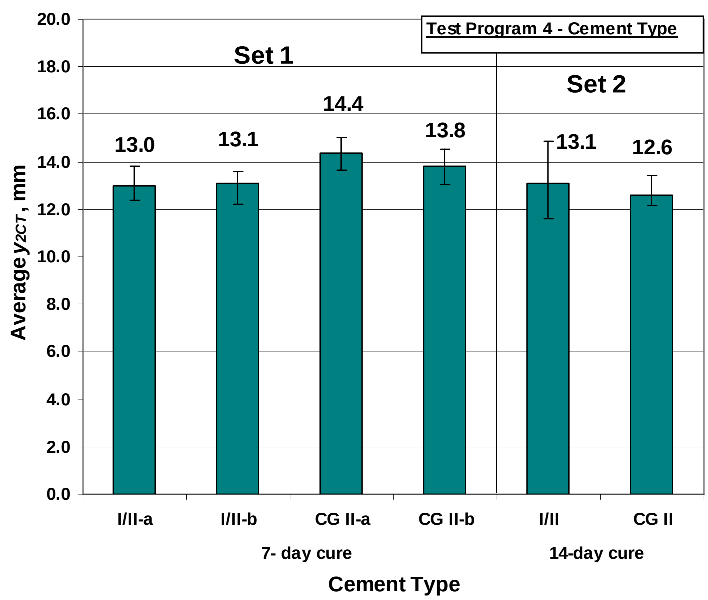


Fig. 3.50 Program 4 Sets 1 and 2 $\overline{y}_{2CT}$ versus Cement Type for concrete with 24.2% paste, a *w/c* ratio of 0.45 and 318 kg/m^3 (535 lb/yd^3) portland cement. Set 1 concrete was cured for 7 days. Set 2 concrete was cured for 14 days.

cement with $\overline{y}_{2CT}$ of 14.4 mm (0.57 in.) are statistically significant (Table 3.27b), but not for the coarse ground Type II cement with $\overline{y}_{2CT}$ of 13.8 mm (0.54 in.). The differences 13.1 mm (0.52 in.) and 13.8 mm (0.54 in.) are not statistically significant.

For set 2 (14-day cure), the concrete made with coarse ground Type II cement has a higher D_{eff} value indicating higher permeability, but the difference is not statistically significant (Table 3.28). This may indicate that the effect of the cement type may be reduced when the longer 14-day curing period is utilized. The $\overline{y}_{2CT}$ for set 2 shows the opposite trend, but the difference is also not statistically significant (Table 3.28).

The mean D_{eff} of the two concrete batches containing coarse ground Type II cement and cured for 7 days in set 1 is 1.31 mm^2/day. The D_{eff} of the concrete containing coarse ground Type II cement and cured for 14 days in set 2 is 1.02 mm^2/day. In comparing the relative performance of concrete in sets 1 and 2 that were cast with coarse ground Type II cement (in separate batches), it is apparent that increasing the curing period from 7 to 14 days reduced D_{eff}. The curing period for the concrete made with Type I/II cement did not appear to affect D_{eff} for sets 1 and 2 as the D_{eff} actually increased from 0.84 to 0.93 mm^2/day with an increase in the curing period from 7 to 14 days. The fact that the concretes were cast in separate batches, however, adds an extra variable (a difference in curing period is not the only difference) and differences between the batches of concrete may have affected the results.

Overall, the concrete mixtures containing Type I/II cement have lower permeability and less chloride penetration than equivalent concrete containing coarse ground Type II cement. For the concrete in sets 1 and 2 made with coarse ground Type II cement, a reduction in permeability is observed with an increase in curing from 7 days (set 1) to 14 days (set 2).

Table 3.27 Student's t-Test Results for Program 4 Set 1

(a) D_{eff}

	Cement Type	D_{eff}	Cement Type			
			I/II-a	I/II-b	CG[1] II-a	CG[1] II-b
Cement Type	I/II-a	0.84		N	Y 0.01 (99%)	Y 0.05 (95%)
	I/II-b	0.84			Y 0.01 (99%)	Y 0.06 (94%)
	CG[1] II-a	1.35				N
	CG[1] II-b	1.26				

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

[1] "CG" denotes coarse ground as discussed in Section 3.12.

(b) $\overline{y}_{2CT}$

	Cement Type	$\overline{y}_{2CT}$, mm	Cement Type			
			I/II-a	I/II-b	CG[1] II-a	CG[1] II-b
Cement Type	I/II-a	13.0		N	Y 0.08 (92%)	N
	I/II-b	13.1			Y 0.10 (90%)	N
	CG[1] II-a	14.4				N
	CG[1] II-b	13.8				

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

[1] "CG" denotes coarse ground as discussed in Section 3.12.

Table 3.28 Student's t-Test Results for Program 4 Set 2

	Cement Type	D_{eff}	Cement Type		$\bar{y}_{2CT}$, mm	Cement Type	
			I/II	CG[1] II		I/II	CG[1] II
Cement Type	I/II	0.93		N	13.1		N
	CG[1] II	1.02			12.6		

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."
[1] "CG" denotes coarse ground as discussed in Section 3.12.

3.12.2 Program 4 Sets 3 and 4 (24.4% paste, 0.45 *w/c* ratio, and either Type I/II or Medium Ground Type II Portland Cement)

For the concrete in set 3 (7-day cure), the Fick's profile for the concrete containing Type I/II cement drops below the profile of the concrete containing medium ground Type II cement at about 5 mm (0.20 in.) and remains below for all greater (deeper) depths, as shown in Fig. 3.51. The low profile indicates lower permeability at the deeper levels. $\bar{y}_{2CT}$ for the concrete containing Type I/II cement is smaller (more shallow) than for the concrete containing medium ground Type II cement, also indicating better protection from chloride penetration.

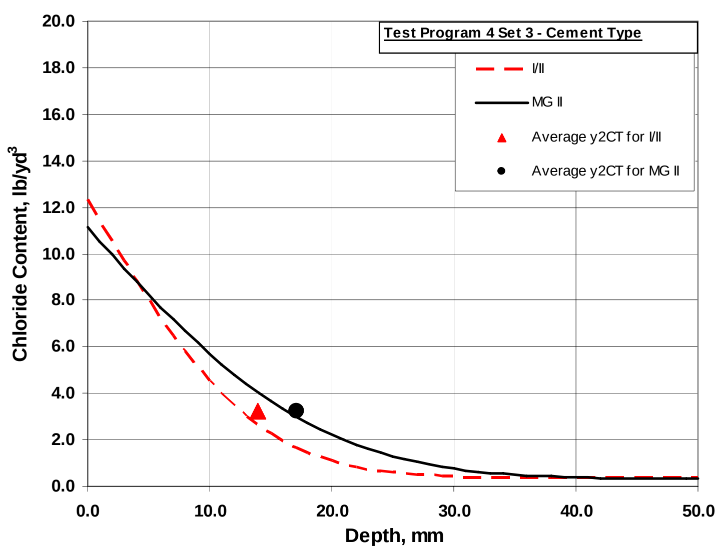


Fig. 3.51 Program 4 Set 3 Fick's profiles and $\bar{y}_{2CT}$ for concrete with Types I/II and medium ground Type II cement, cured for 7-days

For the concrete in set 4 (14-day cure), the Fick's profile for the concrete containing Type I/II cement drops below the profile of the concrete containing medium ground Type II cement at a depth of about 8 mm (0.31 in.) and remains below for all greater (deeper) depths, as shown in Fig. 3.52. $\overline{y}_{2CT}$ for the concrete containing Type I/II cement is smaller (more shallow) than for the concrete containing medium ground Type II cement, also indicating better protection from chloride penetration.

The individual chloride profiles and the y_{2CT} for the concrete batches in set 3 are presented in Figs. B.16 and B.22, and for set 4 in Figs. B.17 and B.23 in Appendix B.

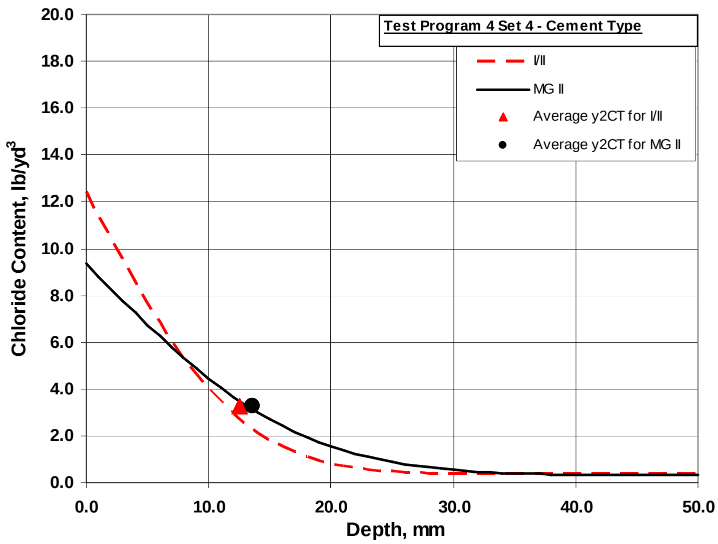


Fig. 3.52 Program 4 Set 4 Fick's profiles and $\overline{y}_{2CT}$ for concrete with Types I/II and medium ground Type II cement, cured for 14 days

The D_{eff} and $\overline{y}_{2CT}$ for sets 3 and 4 are presented graphically in Figs. 3.53 and 3.54.

For set 3 (7-day cure), the concrete made with Type I/II cement has a distinctly lower D_{eff} value (0.63 mm^2/day) than the concrete made with medium ground Type II cement (1.21 mm^2/day) (Fig. 3.53). The D_{eff} values for the concrete made with medium ground Type II cement has the third highest D_{eff} value in the study. The large difference in the D_{eff} values is statistically significant (Table 3.29).

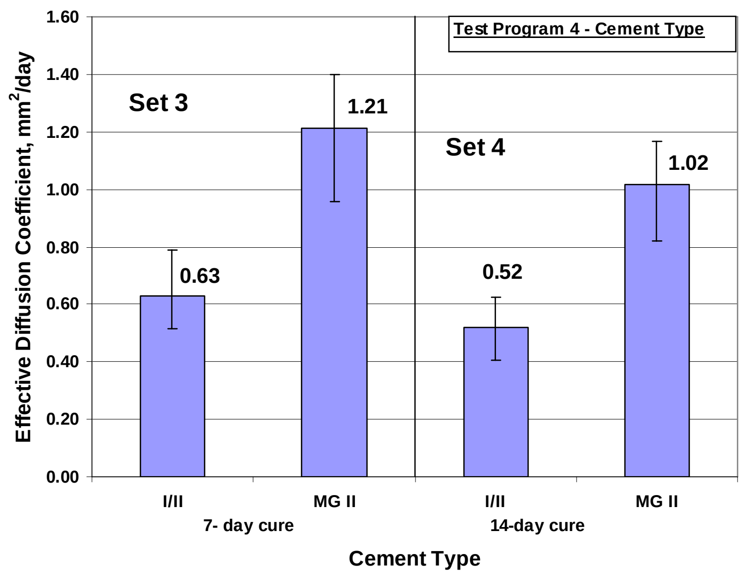


Fig. 3.53 Program 4 Sets 3 and 4 Effective Diffusion Coefficients versus Cement Type for concrete with 24.4% paste, a *w/c* ratio of 0.45 and 318 kg/m^3 (535 lb/yd^3) portland cement. Set 3 concrete was cured for 7 days. Set 4 concrete was cured for 14 days.

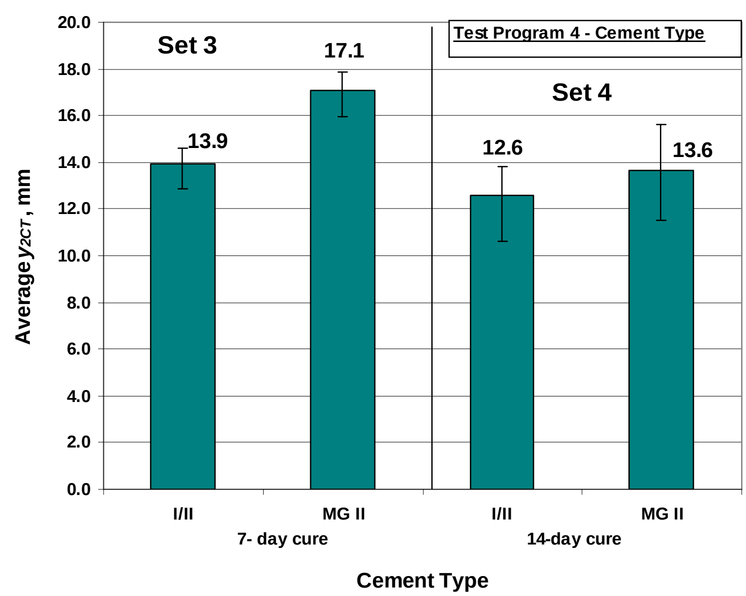


Fig. 3.54 Program 4 Sets 3 and 4 $\overline{y}_{2CT}$ versus Cement Type for concrete with 24.4% paste, a *w/c* ratio of 0.45 and 318 kg/m^3 (535 lb/yd^3) portland cement. Set 3 concrete was cured for 7 days. Set 4 concrete was cured for 14 days.

The $\overline{y}_{2CT}$ values for set 3 follow the same trend, also shown in Table 3.29. The concrete containing medium ground Type II cement has larger $\overline{y}_{2CT}$ values and therefore greater chloride penetration than the concrete containing Type I/II cement. For set 3 (7-days curing), the concrete made with medium ground Type II cement clearly has higher permeability and less resistance to chloride penetration than the concrete made with Type I/II cement.

The set 4 (14-day cure) results follow the same trend as those in set 3. The concrete made with medium ground Type II cement has a significantly higher D_{eff} value (1.02 mm^2/day) than the Type I/II concrete (0.52 mm^2/day) (Fig. 3.53), indicating statistically significant higher permeability (Table 3.30). The $\overline{y}_{2CT}$ results for set 4 also indicate that the concrete containing medium ground Type II cement has a higher chloride penetration, but the difference is not statistically significant.

Table 3.29 Student's t-Test Results for Program 4 Set 3

	Cement Type	D_{eff}	**Cement Type**		$\overline{y}_{2CT}$**, mm**	**Cement Type**	
			I/II	**MG[1] II**		**I/II**	**MG[1] II**
Cement Type	**I/II**	0.63		Y 0.03 (97%)	13.9		Y 0.02 (98%)
	MG[1] II	1.21			17.1		

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."
[1] "MG" denotes medium ground as discussed in Section 3.12.

Table 3.30 Student's t-Test Results for Program 4 Set 4

	Cement Type	D_{eff}	**Cement Type**		$\overline{y}_{2CT}$**, mm**	**Cement Type**	
			I/II	**MG[1] II**		**I/II**	**MG[1] II**
Cement Type	**I/II**	0.52		Y 0.02 (98%)	12.6		N
	MG[1] II	1.02			13.6		

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."
[1] "MG" denotes medium ground as discussed in Section 3.12.

Overall, the concretes containing Type I/II cement have lower permeability and greater protection from chloride penetration than the concretes containing medium ground Type II cement.

3.12.3 Program 4 Sets 5 and 6 (23.7% paste, 0.43 *w/c* ratio, and either Type I/II or Medium Ground Type II Portland Cement)

For the concrete in set 5 (7-day cure), the Fick's profiles for the concretes containing Type I/II cement drop below the profile of the concrete containing medium ground Type II cement at about 5 mm (0.20 in.) and remains below for all greater (deeper) depths, as shown in Fig. 3.55. The low profile indicates lower permeability at the deeper levels. The $\overline{y}_{2CT}$ for the concrete containing Type I/II cement is smaller (more shallow) than for the concrete containing medium ground Type II cement, also indicating better protection from chloride penetration.

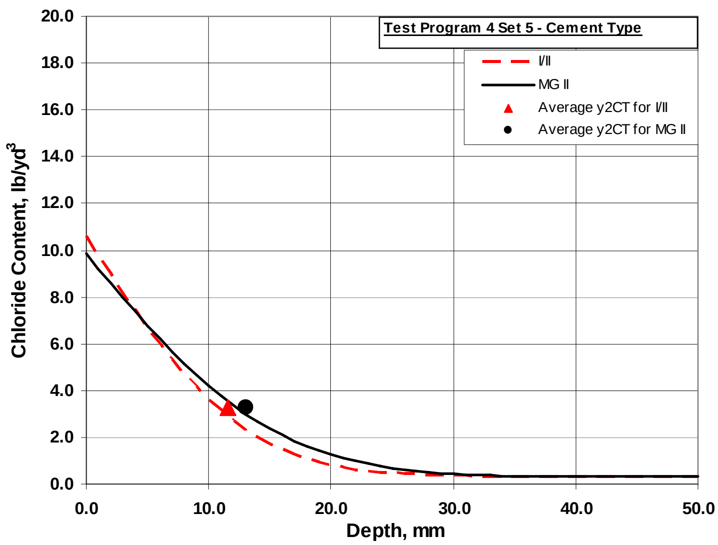


Fig. 3.55 Program 4 Set 5 Fick's profiles and $\overline{y}_{2CT}$ for concrete with Types I/II and medium ground Type II cement, cured for 7-days

For the concrete in set 6 (14-day cure), the Fick's profiles for the concretes containing Type I/II cement drop below the profile of the concrete containing medium ground Type II cement at a depth of about 7 mm (0.28 in.) and remains below for all greater (deeper) depths, as shown in Fig. 3.56. The $\overline{y}_{2CT}$ for the concrete containing Type I/II cement are smaller (more shallow) than for the concrete containing medium ground Type II cement.

The individual chloride profiles and the y_{2CT} depths for the concrete batches in set 5 are presented in Figs. B.14 and B.20, and for set 6 in Figs. B.15 and B.21 in Appendix B.

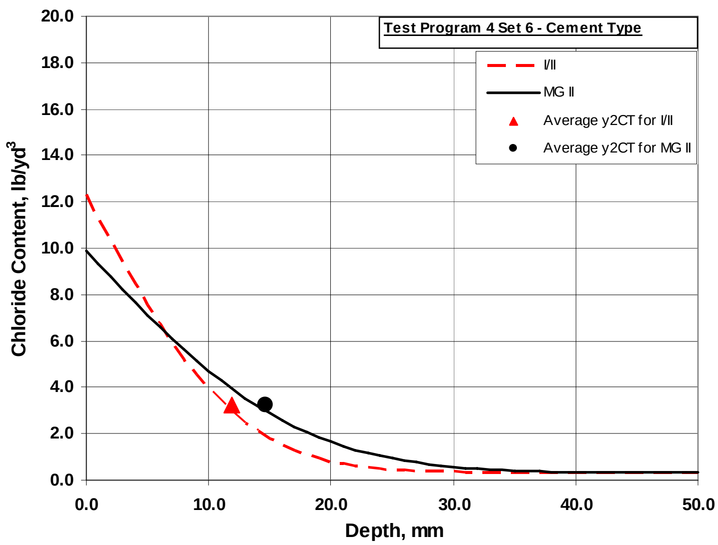


Fig. 3.56 Program 4 Set 6 Fick's profiles and $\overline{y}_{2CT}$ for concrete with Types I/II and medium ground Type II cement, cured for 14 days

The D_{eff} and $\overline{y}_{2CT}$ for sets 5 and 6 are presented graphically in Figs. 3.57 and 3.58.

For set 5 (7-day cure), the concrete made with Type I/II cement has a lower D_{eff} value (0.56 mm^2/day) than the concrete made with medium ground Type II cement (0.82 mm^2/day) (Fig. 3.57). This difference is statistically significant at an $\alpha = 0.06$ (94%) (Table 3.31), indicating that the concrete made with medium ground Type II cements has greater permeability. The $\overline{y}_{2CT}$ values for set 5 exhibits the same trend. The concrete containing medium ground Type II cement has greater chloride penetration than the concrete containing Type I/II cement (Fig. 3.58). For set 5 (7-days curing), the concrete made with medium ground Type II cement has higher permeability and less resistance to chloride penetration than the concrete made with Type I/II cement.

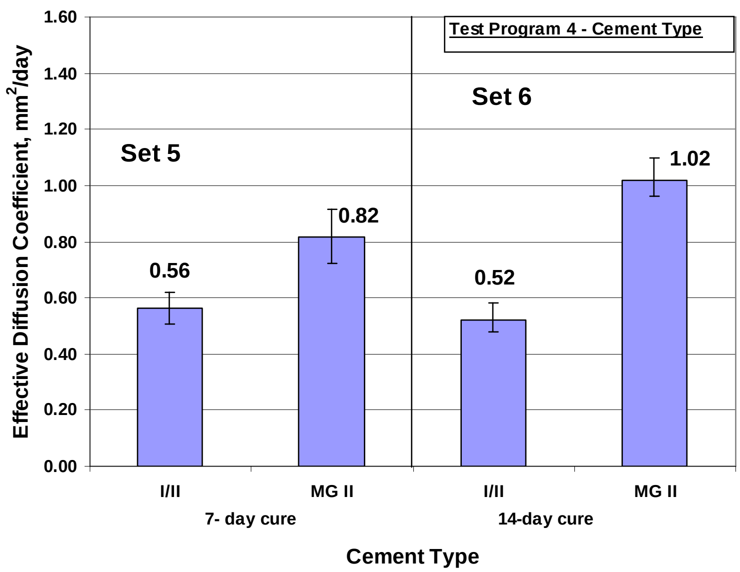


Fig. 3.57 Program 4 Sets 5 and 6 Effective Diffusion Coefficients versus Cement Type for concrete with 23.7% paste, a *w/c* ratio of 0.43 and 318 kg/m^3 (535 lb/yd^3) portland cement. Set 5 concrete was cured for 7 days. Set 6 concrete was cured for 14 days.

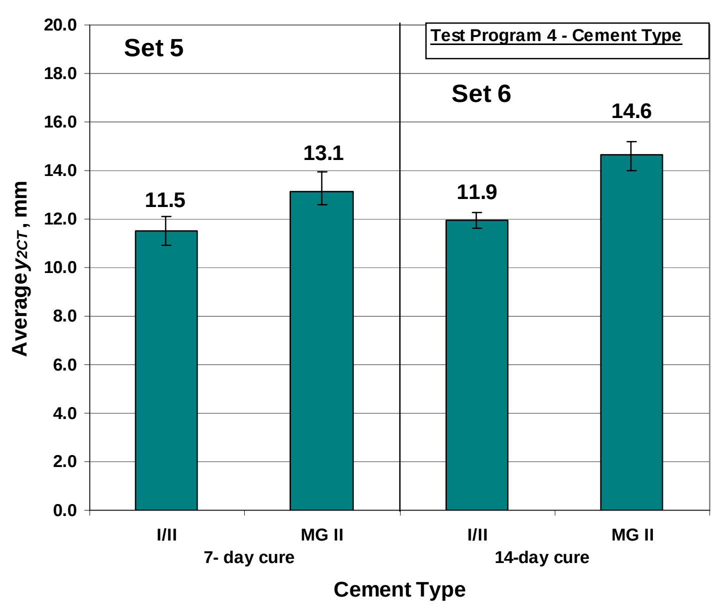


Fig. 3.58 Program 4 Sets 5 and 6 $\bar{y}_{2CT}$ versus Cement Type for concrete with 23.7% paste, a *w/c* ratio of 0.43 and 318 kg/m^3 (535 lb/yd^3) portland cement. Set 5 concrete was cured for 7 days. Set 6 concrete was cured for 14 days.

For set 6 (14-day cure), the results follow the same trend as those in set 5. The concrete made with medium ground Type II cement has significantly higher D_{eff} values (1.02 mm^2/day) than the concrete made with Type I/II cement (0.52 mm^2/day) (Fig. 3.57), and $\overline{y}_{2CT}$ for the concrete containing medium ground Type II cement has a higher $\overline{y}_{2CT}$ value, 14.6 mm (0.57 in.), than the concrete containing Type I/II cement, 11.9 mm (0.47 in.) (Fig. 3.58), following the same trend as D_{eff}. Differences in both performance measures are statistically significant (Table 3.32) at α = 0.01 (99%).

Overall, the concretes in sets 5 and 6 containing Type I/II cement have lower permeability and greater protection from chloride penetration than those containing medium ground Type II cement. The effect of curing for these batches is discussed in Program 2 sets 5 and 6, Section 3.10.4.

Table 3.31 Student's t-Test Results for Program 4 Set 5

	Cement Type	D_{eff}	Cement Type		$\overline{y}_{2CT}$, mm	Cement Type	
			I/II	MG[1] II		I/II	MG[1] II
Cement Type	I/II	0.56		Y 0.06 (94%)	11.5		Y 0.12 (88%)
	MG[1] II	0.82			13.1		

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."
[1] "MG" denotes medium ground as discussed in Section 3.12.

Table 3.32 Student's t-Test Results for Program 4 Set 6

	Cement Type	D_{eff}	Cement Type		$\overline{y}_{2CT}$, mm	Cement Type	
			I/II	MG[1] II		I/II	MG[1] II
Cement Type	I/II	0.52		Y 0.01 (99%)	11.9		Y 0.01 (99%)
	MG[1] II	1.02			14.6		

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."
[1] "MG" denotes medium ground as discussed in Section 3.12.

3.12.4 Program 4 Sets 7 and 8 (23.1% paste, 0.41 *w/c* ratio, and either Type I/II or Medium Ground Type II Portland Cement)

For the concrete in set 7 (7-day cure), the Fick's profile for the concretes containing Type I/II cement has a higher surface concentration and drops below (but just barely so) that of the concrete containing the medium ground Type II cement at about 15 mm (0.59 in.), as shown in Fig. 5.59. At the greater (deeper) depths, the profiles are very similar indicating little difference in the permeability at the deeper levels. The $\overline{y}_{2CT}$ values are approximately the same indicating similar amounts of chloride penetration.

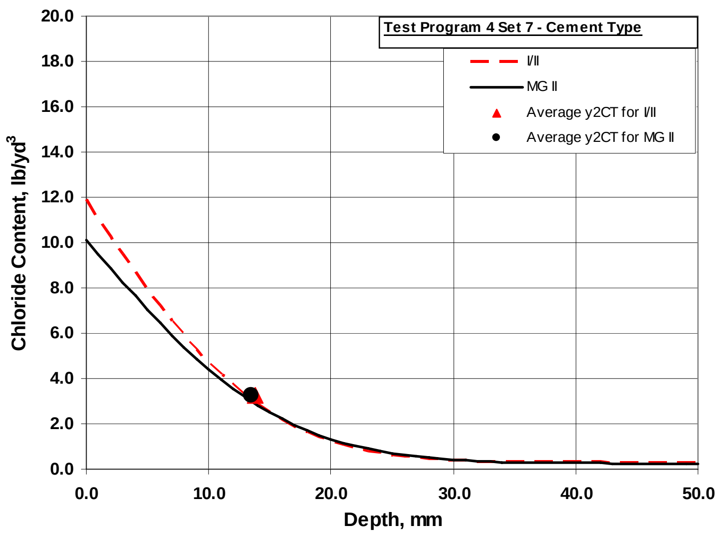


Fig. 3.59 Program 4 Set 7 Fick's profiles and $\overline{y}_{2CT}$ for concrete with Types I/II and medium ground Type II cement, cured for 7-days

For the concrete in set 8 (14-day cure), the Fick's profiles for the concretes containing medium ground Type II cement is below the profile of the concrete containing Type I/II cement throughout the entire depth range, as shown in Fig. 3.60. The lower profile indicates that the medium ground Type II concrete has lower permeability than the concrete containing Type I/II cement. $\overline{y}_{2CT}$ for the concrete containing medium ground Type II cement is smaller (more shallow) than for the concrete containing Type I/II cement, also indicating better protection from chloride penetration. These results do not agree with those for sets 3 through 6, but as will be demonstrated, the differences exhibited in both sets 7 and 8 as a function of cement type are not statistically significant.

The individual chloride profiles and the y_{2CT} for the concrete batches in set 7 are presented in Figs. B.12 and B.18, and for set 8 in Figs. B.13 and B.19 in Appendix B.

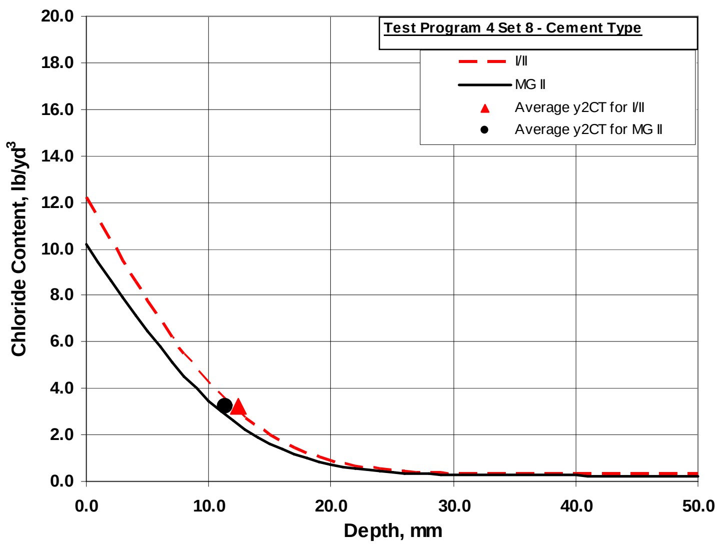


Fig. 3.60 Program 4 Set 8 Fick's profiles and $\overline{y}_{2CT}$ for concrete with Types I/II and medium ground Type II cement, cured for 14 days

The D_{eff} and $\overline{y}_{2CT}$ for sets 7 and 8 are presented graphically in Figs. 3.61 and 3.62.

For set 7 (7-day cure), the concrete made with Type I/II cement has a lower D_{eff} value (0.72 mm^2/day) than the concrete made with medium ground Type II cement (0.88 mm^2/day) (Fig. 3.61). This difference, however, is not apparent from the curves in Fig. 3.59, and is not statistically significant (Table 3.33) due to the scatter in the medium ground Type II results. The $\overline{y}_{2CT}$ results for set 8 exhibit the opposite trend, with the concrete containing medium ground Type II cement having a slightly smaller $\overline{y}_{2CT}$ than the concrete containing Type I/II cement (Fig. 3.62). None of the results for set 7 are statistically significant (Table 3.33) and therefore the results are unclear.

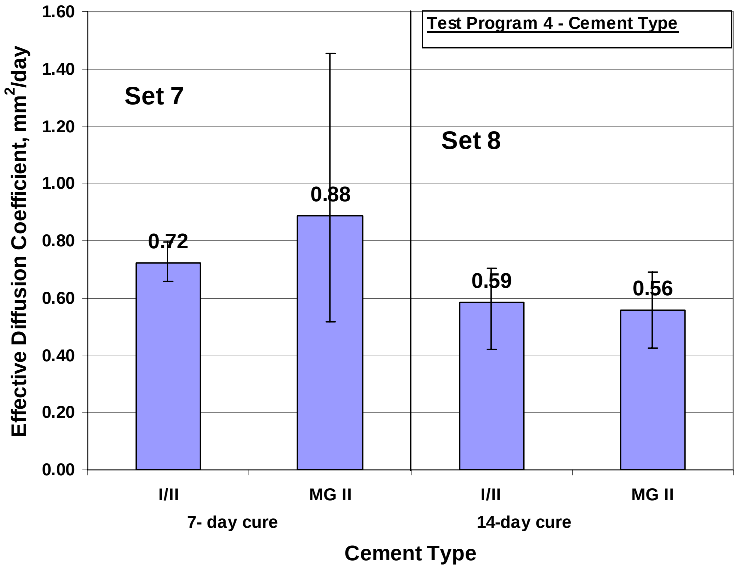


Fig. 3.61 Program 4 Sets 7 and 8 Effective Diffusion Coefficients versus Cement Type for concrete with 23.1% paste, a *w/c* ratio of 0.41 and 318 kg/m^3 (535 lb/yd^3) portland cement. Set 7 concrete was cured for 7 days. Set 8 concrete was cured for 14 days.

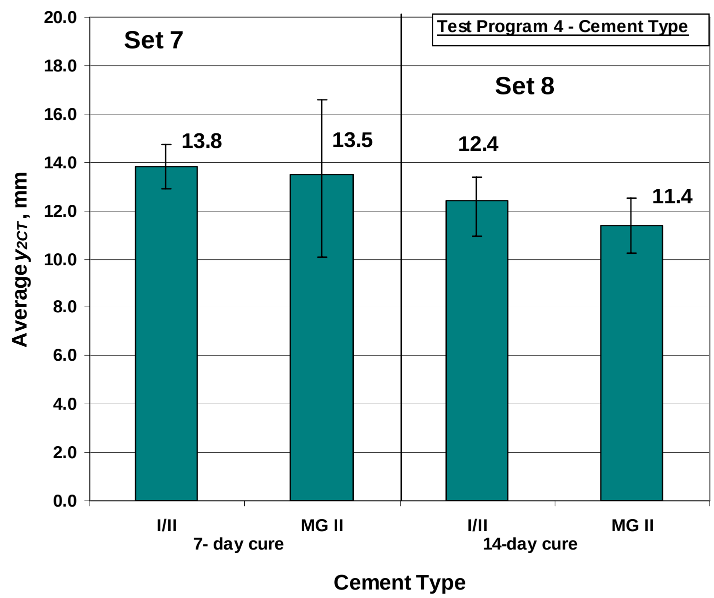


Fig. 3.62 Program 4 Sets 7 and 8 $\overline{y}_{2CT}$ versus Cement Type for concrete with 23.1% paste, a *w/c* ratio of 0.41 and 318 kg/m^3 (535 lb/yd^3) portland cement. Set 7 concrete was cured for 7 days. Set 8 concrete was cured for 14 days.

For set 8 (14-day cure), the results are also somewhat unclear. The concrete made with medium ground Type II cement has a slightly lower D_{eff} value (0.56 mm^2/day) than the concrete containing Type I/II cement (0.59 mm^2/day) (Fig. 3.61). The $\bar{y}_{2CT}$ results follow the same trend (Fig. 3.60) and none of the differences for sets 7 and 8 are statistically significant (Tables 3.33 and 3.34). For these sets, there appears to be no discernable differences as a function of cement type.

Table 3.33 Student's t-Test Results for Program 4 Set 7

	Cement Type	D_{eff}	Cement Type		$\bar{y}_{2CT}$, mm	Cement Type	
			I/II	MG[1] II		I/II	MG[1] II
Cement Type	I/II	0.72		N	13.8		N
	MG[1] II	0.88			13.5		

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."
[1] "MG" denotes medium ground as discussed in Section 3.12.

Table 3.34 Student's t-Test Results for Program 4 Set 8

	Cement Type	D_{eff}	Cement Type		$\bar{y}_{2CT}$, mm	Cement Type	
			I/II	MG[1] II		I/II	MG[1] II
Cement Type	I/II	0.59		N	12.4		N
	MG[1] II	0.56			11.4		

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."
[1] "MG" denotes medium ground as discussed in Section 3.12.

3.12.5 Program 4 – Summary

The results from six of the eight sets in Program 4 indicate that concrete made with the coarse and medium ground Type II cement has greater permeability and more chloride penetration than those cast with Type I/II cement, while the results from two of the sets showed no discernable difference in the permeability of concrete made with the medium ground Type II cement from that of Type I/II cement.

3.13 PROGRAM 5 – MINERAL ADMIXTURES

The use of mineral admixtures in concrete is generally recognized as an effective method to reduced concrete permeability and increase protection from chloride penetration. Program 5 includes six sets of concrete mixtures examining the effect of Grades 100 (G100) and 120 (G120) ground granulated blast furnace slag (GGBFS) and silica fume on the resistance of concrete to chloride penetration. All of the mixtures in Program 5 were cast with a *w/cm* ratio of 0.42 and cured for 14 days. Additional Program 5 details are provided in Section 2.7.1. Mixture proportions, plastic concrete properties and compressive strengths are provided in Appendix A.

A summary of Program 5 is provided in Table 3.35. All sets include a control batch containing no mineral admixture. Set 1 includes mixtures containing G100 and G120 GGBFS in binary mixtures at a 60% replacement level. Set 2 examines the performance of G120 GGBFS at 30% and 60% replacement levels. Set 3 examines the performance of silica fume at 3% and 6% replacement levels. Sets 4 through 6 include binary (GGBFS and cement) and ternary (GGBFS, silica fume, and cement) mixtures at different total paste contents. The concrete mixtures in sets 4 and 5 have paste contents of 23.3% and 21.6%, respectively. The concrete mixtures in set 4 contain G100 GGBFS and silica fume, while the concrete mixtures in set 5 contains G120 GGBFS and silica fume. Similar to sets 4 and 5, set 6 examines binary and ternary mixtures, but also introduces reduced paste contents and a ternary mixture with higher GGBFS content. Set 6 includes binary and ternary mixtures with decreasing paste contents to determine whether the decrease in permeability due to the mineral admixtures is enough to make up for the loss in permeability due to reduced paste. As seen in Program 1, for concretes containing no mineral admixtures, lower paste contents are generally associated with having higher permeability. The results of set 6 indicate that both binary and ternary mixtures at reduced paste contents have lower permeability than the control mixtures. The decrease in permeability from the presence of mineral admixtures is greater than the loss in permeability due to the reduced paste content.

Table 3.35 Program 5 – Summary

Set	Paste Content, %	Mineral Admixture	Replacement Level, %
1	23.3	None - control G100 GGBFS G120 GGBFS	0 60 60
2	23.3	G120 GGBFS	0 30 60
3	23.3	Silica Fume	0 3 6
4	23.3	G100 GGBFS-Silica Fume	0-0 60-0 60-6
5	21.6	G120 GGBFS-Silica Fume	0-0 60-0 60-6
6	23.3 21.6 21.6 20.5 20.5	G120 GGBFS-Silica Fume	0-0 0-0 60-0 60-6 80-6

The results of Program 5 indicate that the presence of GGBFS and silica fume at all the replacement levels examined in this study reduces the permeability of concrete.

3.13.1 Program 5 Set 1 (Grade of GGBFS)

Set 1 examines the permeability of two grades of GGBFS (G100 and G120) used in binary mixtures. All the concrete in set 1 has 23.3% paste content and a *w/cm* ratio of 0.42. For the concrete in set 1, the Fick's profile for the concrete containing G100 GGBFS is below the profiles for the concrete containing G120 GGBFS and the concrete containing no mineral admixtures, throughout the depth, as shown in Fig. 3.6.3. This indicates that the concrete containing G100 GGBFS has the lowest overall permeability. The $\overline{y}_{2CT}$ for the concrete containing G100 GGBFS is also the smallest (most shallow), also indicating the best resistance to chloride penetration. The profile of the concrete containing G120 GGBFS has the highest surface concentration and the highest background chloride concentration. The Fick's profile of the concrete containing G120 GGBFS drops below the profile of the control mixture from approximately 7 to 17 mm (0.28 to 0.67 in.). The control mixture has slightly lower background levels, so it has lower chloride concentrations for depths greater than approximately 17 mm (0.67 in.). The control mixture containing no GGBFS exhibits the largest (deepest) $\overline{y}_{2CT}$, indicating greater chloride penetration than those containing GGBFS. The individual chloride profiles and the y_{2CT} for the concrete in set 1 are presented in Figs. B.28, B.24 and B.29 in Appendix B.

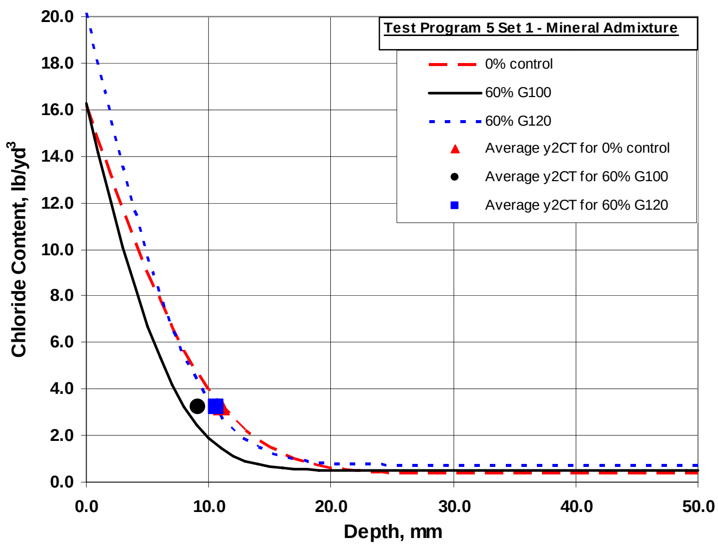


Fig. 3.63 Program 5 Set 1 Fick's profiles and $\overline{y}_{2CT}$ for concrete containing Grade 100 or 120 GGBFS

The D_{eff} and $\overline{y}_{2CT}$ for set 1 are presented graphically in Figs. 3.64 and 3.65.

For set 1, a reduction in permeability is seen with the 60% replacement of cement with both G100 and G120 GGBFS. As shown in Fig. 3.64, D_{eff} is reduced from 0.38 mm^2/day for the control mixture containing no GGBFS to 0.19 mm^2/day with 60% G100 GGBFS, and from 0.38 to 0.26 mm^2/day for G120 GGBFS. Both differences are statistically significant at α = 0.05 (95%) or lower (Table 3.36). The mixture containing G100 GGBFS exhibits better performance than the G120 GGBFS mixture, as it has the lowest D_{eff}. The latter difference is statistically significant at α = 0.06 (94%) (Table 3.36). The same trend is seen for the $\overline{y}_{2CT}$ in Fig. 3.65. A

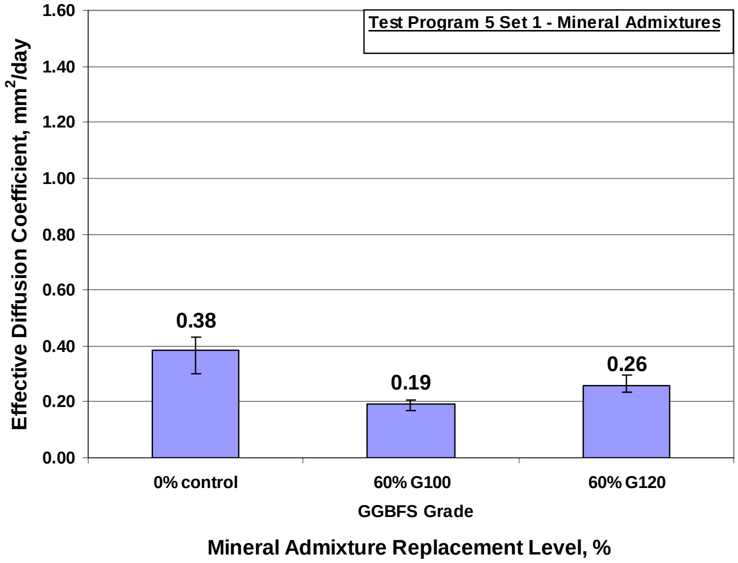


Fig. 3.64 Program 5 Set 1 Effective Diffusion Coefficients versus Grade of GGBFS for concrete containing 60% GGBFS

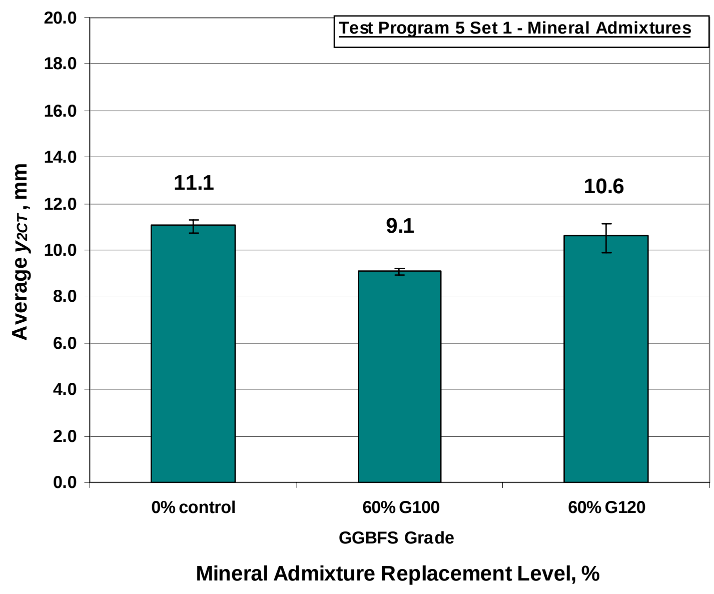


Fig. 3.65 Program 5 Set 1 $\overline{y}_{2CT}$ versus Grade of GGBFS for concrete containing 60% GGBFS

reduction in the chloride penetration is observed with the 60% cement replacement with GGBFS of either grade. The mixture containing G100 GGBFS exhibits the lowest chloride penetration. The difference in $\overline{y}_{2CT}$ between the control mixture and the G100 GGBFS mixture is statistically significant at a significance level of α of 0.01 (99%) and between the G100 and G120 mixtures at α of 0.02 (98%) (Table 3.36). No significant difference is observed between the control mixture and the concrete containing G120 GGBFS, but the trend does generally agree with the D_{eff} results in this set.

Overall, the G100 GGBFS mixture, with the lowest D_{eff} and $\overline{y}_{2CT}$ values has the best performance in set 1. The replacement of 60% of the cement with GGBFS , however, improves the permeability performance of the concrete for both grades of GGBFS.

Table 3.36 Student's t-Test Results for Program 5 Set 1

	Replacement Level, %	D_{eff}	Mineral Admixture			$\overline{y}_{2CT}$, mm	Mineral Admixture		
			0%	60% G100	60% G120		0%	60% G100	60% G120
Mineral Admixture	0%	0.38		Y 0.02 (98%)	Y 0.05 (95%)	11.1		Y 0.01 (99%)	N
	60% G100	0.19			Y 0.06 (94%)	9.1			Y 0.02 (98%)
	60% G120	0.26				10.6			

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

3.13.2 Program 5 Set 2 (Replacement Level of Grade 120 GGBFS)

Set 2 examines the permeability performance of various replacement levels of cement with G120 GGBFS. All of the concrete in set 2 has a paste content of 23.3% and a *w/cm* ratio of 0.42. For the concrete in set 2, the Fick's profile for the concrete containing 30% G120 GGBFS is generally below the other profiles, indicating the lowest overall permeability, as shown in Fig. 3.66. $\overline{y}_{2CT}$ for the 30% G120 GGBFS profile is also the smallest (most shallow), also indicating the best resistance to chloride penetration. The profile of the concrete containing 60% G120 GGBFS has the highest surface concentration (greater than 20 lb/yd^3) and the highest background chloride concentration in set 2. This high surface concentration is typical behavior for concretes with the lowest permeability in this study. The high surface concentration can indicate a build up of chlorides near the surface due to the lack of chlorides diffusing deeper into the concrete. The chlorides get stuck near the surface instead of diffusing down into the concrete. The Fick's profile drops quickly to low chloride concentrations deeper in the concrete. The 60% G120 profile drops below the profile of the control mixture from approximately 7 to 18 mm (0.28 to 0.71 in.). The control mixture (0% GGBFS) has the lowest background levels at depths greater than approximately 18 mm (0.71 in.). The control mixture exhibits the largest $\overline{y}_{2CT}$, indicating greater chloride penetration than those containing the GGBFS. The individual chloride profiles and the y_{2CT} for the concrete in set 2 are presented in Figs. B.28, B.40 and B.29 in Appendix B.

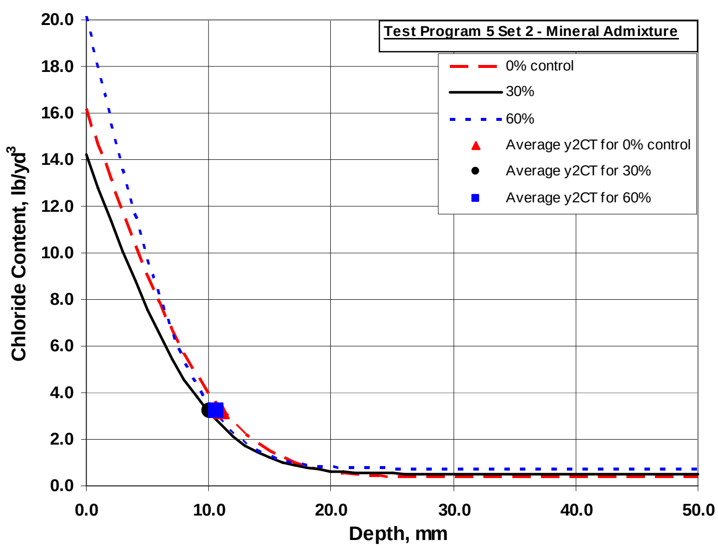


Fig. 3.66 Program 5 Set 2 Fick's profiles and $\overline{y}_{2CT}$ for concrete containing Grade 120 GGBFS

The D_{eff} and $\overline{y}_{2CT}$ for set 2 are presented graphically in Figs. 3.67 and 3.68.

For set 2, a reduction in permeability is observed with increasing replacement levels. As shown in Fig. 3.67, D_{eff} is reduced from 0.38 mm^2/day for the control mixture containing no slag to 0.34 mm^2/day with the addition of 30% GGBFS, and from 0.38 to 0.26 mm^2/day for 60% replacement. The difference between the control and 60% replacement is statistically significant at $\alpha = 0.05$ (95%) (Table 3.37), but the differences between the control and 30% replacement and between the 30% and 60% replacements are not statistically significant.

A large amount of scatter is observed in the $\overline{y}_{2CT}$ results (Fig. 3.68) for the concrete containing 30% G120 GGBFS. A reduction in $\overline{y}_{2CT}$ is observed between the control mixture and each replacement level, but the differences are not statistically significant. An increase in the $\overline{y}_{2CT}$ is observed with an increase in the replacement level from 30% to 60%, but again the differences are not statistically significant (Table 3.37) and the increase may be due to the scatter in the 30% G120 GGBFS mixture results.

Overall, set 2 results indicate a trend toward decreased permeability at both the 30% and 60% replacement levels with Grade 120 GGBFS, although most of the differences were not statistically significant. The concrete containing 60% Grade 120 GGBFS had a statistically significant decrease in the diffusion coefficient compared to the control mixture.

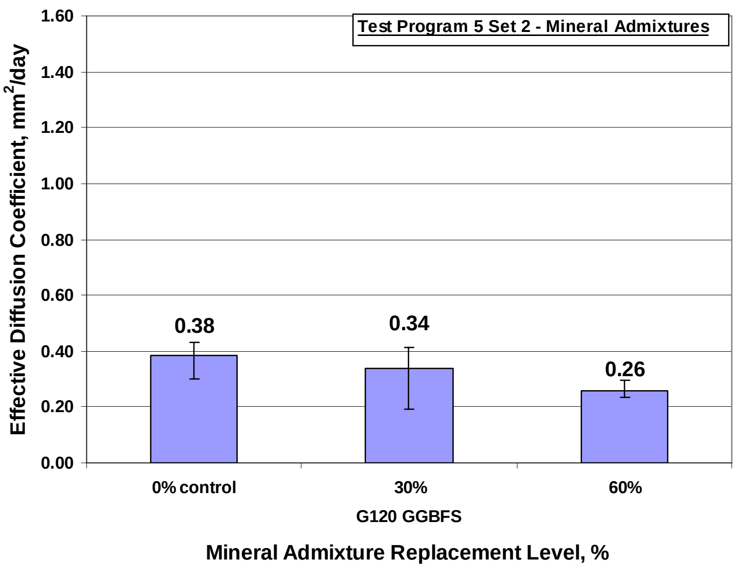


Fig. 3.67 Program 5 Set 2 Effective Diffusion Coefficients versus Replacement Level % for concrete containing Grade 120 GGBFS

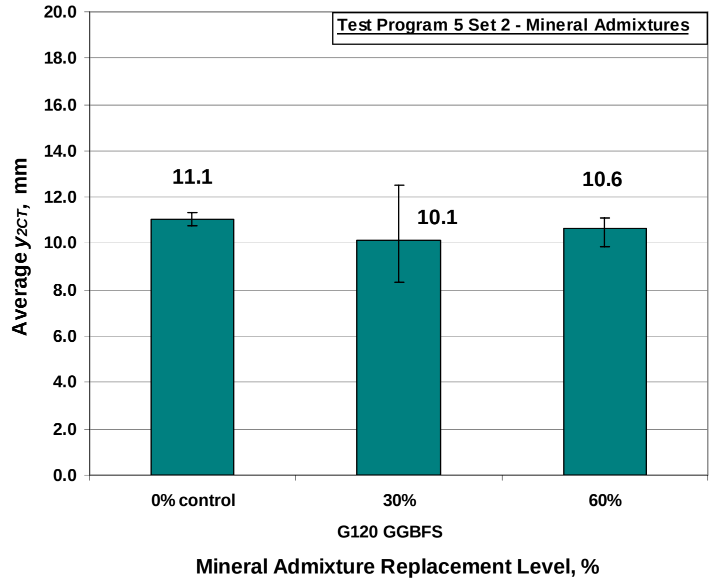


Fig. 3.68 Program 5 Set 2 $\overline{y}_{2CT}$ versus Replacement Level % for concrete containing Grade 120 GGBFS

Table 3.37 Student's t-Test Results for Program 5 Set 2

	Replacement Level, %	D_{eff}	**Mineral Admixture**			$\overline{y}_{2CT}$, **mm**	**Mineral Admixture**		
			0%	**30% G120**	**60% G120**		**0%**	**30% G120**	**60% G120**
Mineral Admixture	**0%**	0.38		N	Y 0.05 (95%)	11.1		N	N
	30% G120	0.34			N	10.1			N
	60% G120	0.26				10.6			

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

3.13.3 Program 5 Set 3 (Replacement Levels of Silica Fume)

Set 3 examines the permeability of binary mixtures containing 3% or 6% silica fume (SF) with a paste content of 23.3% and a *w/cm* ratio of 0.42. It is generally understood that SF reduces the permeability of concrete. For the concrete in set 3, however, there appears to be little affect on permeability of including silica fume, and the Fick's profiles for the 0% control mixture and the 6% SF are virtually identical.

The 3% SF mixture has the lowest surface concentration values in set 3, as shown in Fig. 3.67. The profile for this mixture crosses above the other profiles at approximately 9 mm (0.35 in.) and remains higher at the deeper levels. The $\overline{y}_{2CT}$ values are nearly identical, with the 3% SF mixture having the greatest (deepest) chloride penetration and the control mixture having the smallest (most shallow) penetration. The individual chloride profiles and the y_{2CT} for the concrete in set 3 are presented in Figs. B.28, B.36 and B.35 in Appendix B.

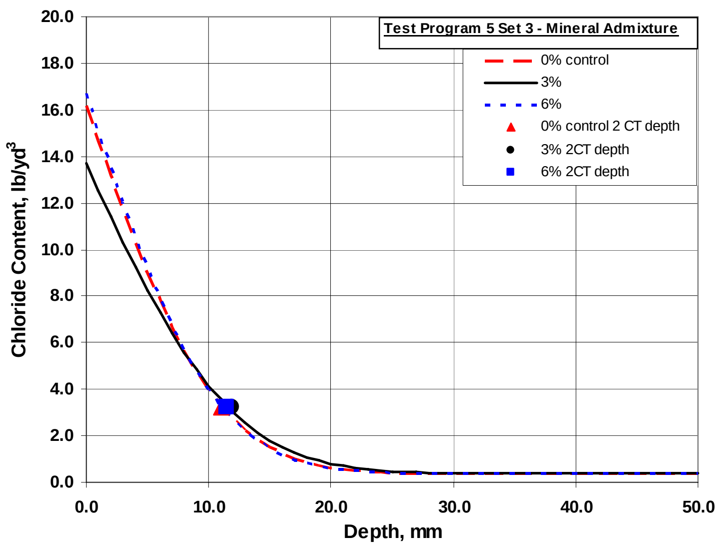


Fig. 3.69 Program 5 Set 3 Fick's profiles and $\overline{y}_{2CT}$ for concrete containing Silica Fume

The D_{eff} and $\overline{y}_{2CT}$ for set 3 are presented graphically in Figs. 3.70 and 3.71.

In the same manner as for the Fick's profiles, at 0.38 and 0.37 mm^2/day, respectively, the D_{eff} results for the control mixture and the 6% SF mixture are virtually identical, indicating similar permeabilities. At 11.1 and 11.5 mm, the $\overline{y}_{2CT}$ results are also very similar. Because it is generally understood that silica fume reduces the permeability of concrete, it is anticipated that the 0% control mixture should have the higher D_{eff} and, therefore, the highest permeability. This is not the case for the set 3 results. In fact, the D_{eff} results for the 0% control mixture are lower

(0.38 mm^2/day) than the 3% SF mixture (0.48 mm^2/day) (Fig. 3.70). The expected decrease in D_{eff} does exist as the replacement level increases from 3% to 6% SF. However, there is an unexplained increase in D_{eff} as the replacement level increases from 0% to 3% SF. This inconsistency may be the strongest indicator that the 0% control D_{eff} results may be low. For example, D_{eff} for the control mixture in set 3 is lower than D_{eff} for similar mixtures in Program 3. When compared with the Program 3 set 2 results for mixtures with *w/c* ratios of 0.41, 0.43, and 0.45 (D_{eff} values of 0.59, 0.52, and 0.52, see Fig. 3.35), D_{eff} for the control mixture (0.42 *w/c* ratio) is low. Along this line, this control mixture is also used in Program 3 set 5 (Fig. 3.44), where the comparison with mixtures with lower *w/c* ratios indicates that the permeability of this batch of concrete is lower than should be expected.

Because the results of the control mixture may be questionable, it is important to consider the relative performances of the mixtures containing 3% and 6% SF.

An increase in the replacement level from 3% to 6% SF resulted in a decrease in the D_{eff} from 0.48 to 0.37 mm^2/day (Fig. 3.70). This difference is statistically significant at a significance level of $\alpha = 0.04$ (96%) (Table 3.38). There is also a decrease in the $\overline{y}_{2CT}$ value from 11.9 to 11.5 mm (0.47 to 0.45 in.) (Fig. 3.71), although this difference is not statistically significant (Table 3.38).

Overall, it is observed that the concrete containing 6% SF has lower permeability and less chloride penetration than the concrete containing 3% SF. The 0% control mixture may have lower than expected permeability characteristics.

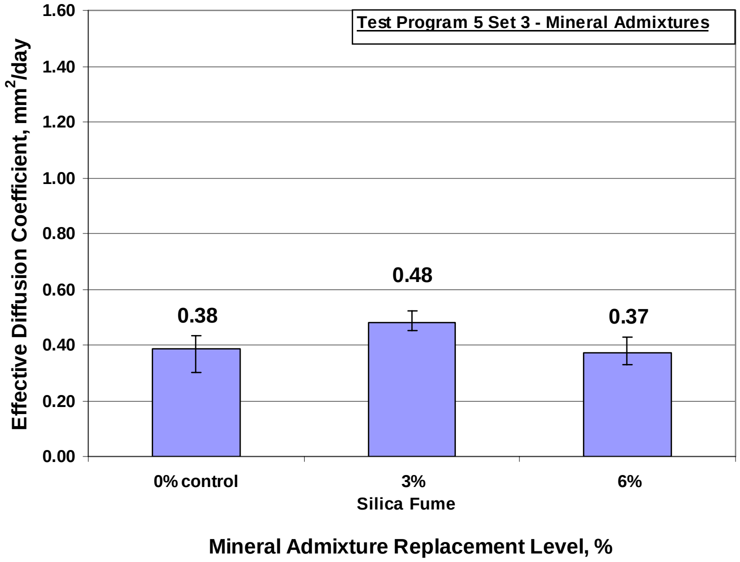


Fig. 3.70 Program 5 Set 3 Effective Diffusion Coefficients versus Replacement Level % for concrete containing Silica Fume

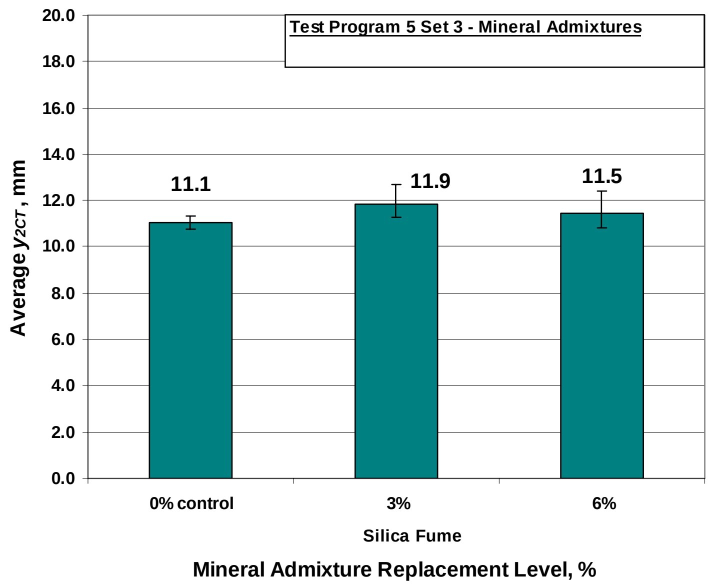


Fig. 3.71 Program 5 Set 3 $\overline{y}_{2CT}$ versus Replacement Level % for concrete containing Silica Fume

Table 3.38 Student's t-Test Results for Program 5 Set 3

	Replacement Level, %	D_{eff}	Mineral Admixture			$\overline{y}_{2CT}$, mm	Mineral Admixture		
			0%	3% SF	6% SF		0%	3% SF	6% SF
Mineral Admixture	0%	0.38		Y 0.10 (90%)	N	11.1		Y 0.16 (84%)	N
	3% SF	0.48			Y 0.04 (96%)	11.9			N
	6% SF	0.37				11.5			

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

3.13.4 Program 5 Sets 4 and 5 (Binary and Ternary Mixtures Containing Grades 100 or 120 GGBFS, and Silica Fume)

Sets 4 and 5 examine the permeability of binary and ternary mixtures at constant paste contents. The concrete in set 4 has 23.3% paste and contains Grade 100 (G100) GGBFS, while the concrete in set 5 has 21.6% paste and contains Grade 120 (G120) GGBFS. Both sets have a *w/cm* ratio of 0.42, and the ternary mixtures contain silica fume (SF).

For the concrete in set 4, the Fick's profile for the 0% control mixture is clearly above (higher) than the other profiles, indicating higher permeability, as shown in Fig. 3.72. $\overline{y}_{2CT}$ for the control mixture is the greatest (deepest), indicating the greatest chloride penetration for the set. The profile of the ternary mixture with 60% GGBFS and 6% SF is the lowest of the set, and $\overline{y}_{2CT}$ is the smallest (most shallow) indicating the lowest permeability and least chloride penetration. Fick's profile and the $\overline{y}_{2CT}$ results for the binary mixture containing 60% G100 GGBFS indicate a permeability somewhere between that of the control and the ternary mixtures. The individual chloride profiles and the y_{2CT} depths for the concrete in set 4 are presented in Figs. B.28, B.24 and B.34 in Appendix B.

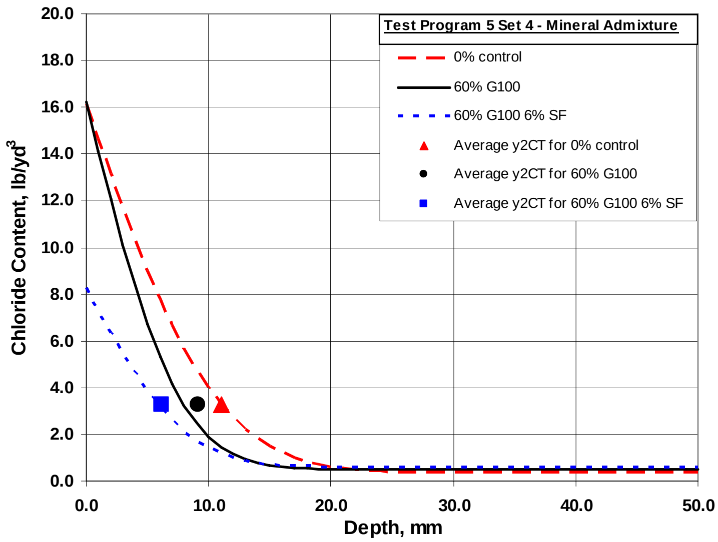


Fig. 3.72 Program 5 Set 4 Fick's profiles and $\overline{y}_{2CT}$ for binary and ternary concrete mixtures with 23.3% paste and including G100 GGBFS or Silica Fume

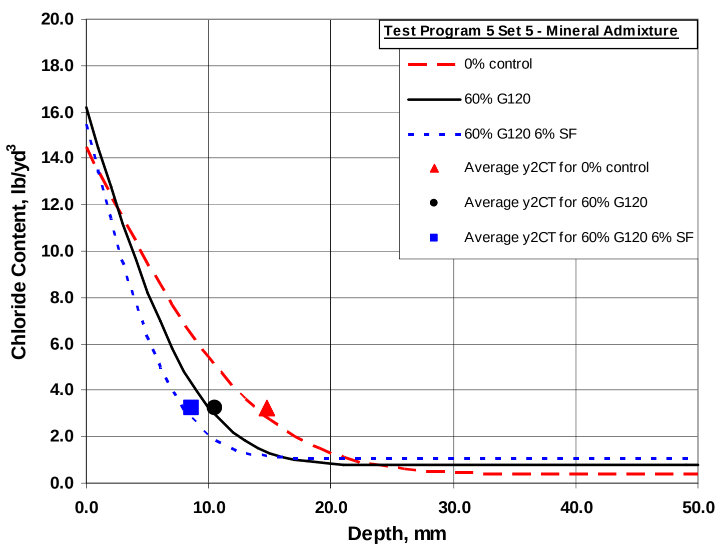


Fig. 3.73 Program 5 Set 5 Fick's profiles and $\overline{y}_{2CT}$ for binary and ternary concrete mixtures with 21.6% paste and including G120 GGBFS or Silica Fume

For the concrete in set 5, the Fick's profiles for the control mixture has the lowest surface concentration, but crosses the other profiles and is clearly above (higher) than the other profiles at depths greater than approximately 3 mm (0.12 in.), as shown in Fig. 3.73. This indicates that the control mixture has the highest permeability in set 5. Just as for set 4, the profile of the ternary mixture in set 5 is the lowest, indicating the least permeability. The binary mixture again lies in the middle. The $\overline{y}_{2CT}$ results for set 5 indicate the same trend. The individual chloride profiles and the y_{2CT} depths for the concrete in set 5 are presented in Figs. B.39, B.30 and B.31 in Appendix B.

The D_{eff} and $\overline{y}_{2CT}$ for sets 4 and 5 are presented graphically in Figs. 3.74 and 3.75.

For set 4, the 60% replacement of cement with G100 GGBFS resulted in a decrease in the D_{eff} from 0.38 to 0.19 mm^2/day (Fig. 3.74). The replacement of cement with 60% G100 GGBFS and 6% SF resulted in a decrease in the D_{eff} from 0.38 to 0.22 mm^2/day. The difference in D_{eff} between the control and the binary mixtures was statistically significant at $\alpha = 0.02$ (98%) and between the control and the ternary mixtures at $\alpha = 0.05$ (95%) (Table 3.39). Unexpectedly, the D_{eff} for the ternary mixture was higher than for the binary mixture for this set. This is related to (or influenced by) the high surface concentration on Fick's profile for the binary mix. The $\overline{y}_{2CT}$ values for set 4 follow a similar trend. The control mixture has the highest $\overline{y}_{2CT}$ and, in this case, the ternary mixture has the lowest $\overline{y}_{2CT}$. All differences in $\overline{y}_{2CT}$ were statistically significant for set 4 (Table 3.39).

The results for set 5 clearly indicate that both the binary and ternary mixtures have lower permeabilities than the control mixture, and the ternary mixture has the lowest permeability of the set. When compared to the control mixture containing no mineral admixtures, the 60% replacement of cement with G120 GGBFS resulted in a decrease in the D_{eff} from 0.65 to 0.28 mm^2/day (Fig. 3.74). The replacement of cement with 60% G120 GGBFS and 6% SF resulted in a decrease from 0.65 to 0.15 mm^2/day. These differences are significant at $\alpha = 0.01$ (99%) (Table 3.40). The $\overline{y}_{2CT}$ values for set 5 follow the same trend. Both the binary and ternary mixtures have lower chloride penetration than the control mixture, and the ternary mixture has the

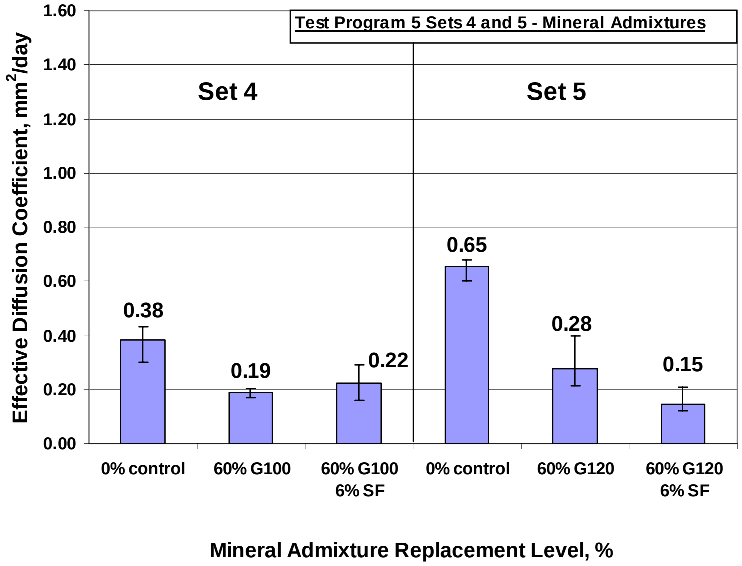


Fig. 3.74 Program 5 Sets 4 and 5 Effective Diffusion Coefficients versus Replacement Level % for binary and ternary concrete mixtures containing GGBFS or silica fume. Set 4 has 23.3% paste and includes G100 GGBFS. Set 5 has 21.6% paste and includes G120 GGBFS.

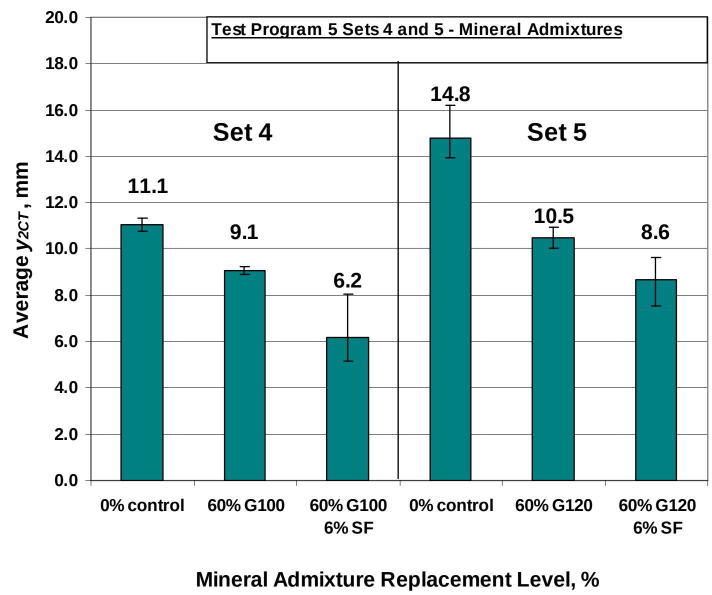


Fig. 3.75 Program 5 Sets 4 and 5 $\overline{y}_{2CT}$ versus Replacement Level % for binary and ternary concrete mixtures containing GGBFS or silica fume. Set 4 has 23.3% paste and includes G100 GGBFS. Set 5 has 21.6% paste and includes G120 GGBFS.

lowest chloride penetration results. All differences in the $\overline{y}_{2CT}$ were statistically significant for set 5 (Table 3.40).

Overall, the set 4 and 5 results indicate that the control mixture containing no mineral admixtures has the highest permeability and highest chloride penetration. All of the Fick's profiles and $\overline{y}_{2CT}$ results, as well as the set 4 D_{eff} results, indicate that the ternary mixtures have the lowest permeability and the least chloride penetration. The use of GGBFS and silica fume in concrete is generally recognized as reducing chloride penetration in concrete. The results from sets 4 and 5 are consistent with these expectations.

Table 3.39 Student's t-Test Results for Program 5 Set 4

	Replacement Levels, %-%	D_{eff}	**Replacement Levels %G100-%SF**			$\overline{y}_{2CT}$**, mm**	**Replacement Levels %G100-%SF**		
			0-0	**60-0**	**60-6**		**0-0**	**60-0**	**60-6**
Replacement Levels %G100-%SF	**0-0**	0.38		Y 0.02 (98%)	Y 0.05 (95%)	11.1		Y 0.01 (99%)	Y 0.01 (99%)
	60-0	0.19			N	9.1			Y 0.04 (96%)
	60-6	0.22				6.2			

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

Table 3.40 Student's t-Test Results for Program 5 Set 5

	Replacement Levels, %	D_{eff}	**Replacement Levels %G120-%SF**			$\overline{y}_{2CT}$**, mm**	**Replacement Levels %G120-%SF**		
			0-0	**60-0**	**60-6**		**0-0**	**60-0**	**60-6**
Replacement Levels %G120-%SF	**0-0**	0.65		Y 0.02 (98%)	Y 0.01 (99%)	14.8		Y 0.03 (97%)	Y 0.01 (99%)
	60-0	0.28			Y 0.15 (85%)	10.5			Y 0.12 (88%)
	60-6	0.15				8.6			

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

In addition to the standard analysis, it is worthwhile to consider the binary mixture in set 3 containing 6% SF alongside the results for set 4 because the paste contents are the same (23.3%). The 6% SF binary mixture in set 3 has a higher D_{eff} (0.37 mm^2/day) (Fig. 3.20) and $\overline{y}_{2CT}$ (11.5 mm)(0.45 in.) (Fig. 3.71) than the 60% G100 GGBFS binary mixture [0.19 mm^2/day and 9.1 mm)(0.34 in.)] in set 4 (Figs. 3.74 and 3.75), indicating that the binary mixture containing 60% G100 GGBFS has a lower permeability than the binary mixture containing 6% SF. Interestingly, the combination of the two mineral admixtures in a ternary mixture produced concrete with lower D_{eff} (0.22 mm^2/day) and $\overline{y}_{2CT}$ (6.2 mm)(0.24 in.) values than for either binary mixture alone. This may indicate a synergistic effect of GGBFS and SF when used together in ternary mixtures, reducing the permeability of the concrete more than either of the two mineral admixtures alone.

3.13.5 Program 5 Set 6 (Reduced Paste Content Binary and Ternary Mixtures Containing G120 GGBFS and Silica Fume)

The increased cohesiveness and workability due to the addition of silica fume in a mixture can generally allow for a reduction of paste content while still maintaining workability and creating a placeable mixture. Because paste is the portion of the concrete that shrinks, it is desirable to minimize the paste content in mixtures to reduce cracking in bridge decks. Set 6 is used to determine whether the addition of silica fume in ternary mixtures with reduced paste contents can compensate for the increase in permeability associated with reduced paste contents (Program 1). Concrete with 23.3% paste containing 100% portland cement is compared with binary and ternary mixtures containing as little as 20.5% paste.

Fick's profiles and $\overline{y}_{2CT}$ values for set 5 are shown in Fig. 3.76. The Fick's profile for the control mixture (no mineral admixture) with 21.6% paste has the highest profile for depths greater than approximately 4 mm (0.16 in.). The control mixture containing 23.3% paste has the next highest profile. Also as expected, of these two mixtures, the mix with the lowest paste content has the highest permeability. This is consistent with the results of Program 1.

Consistent with sets 4 and 5 in this program, the binary mixture containing 60% G120 GGBFS and 21.6% paste has the next highest profile and the ternary mixtures with 20.5% paste, 6% SF and 60 or 80% GGBFS have the lowest profiles, indicating the lowest permeabilities. Interestingly, the profile of the ternary mixture with 60% G120 GGBFS has a higher surface concentration and a lower background concentration than the ternary mixture with 80% G120 GGBFS. The profile of the 60% ternary mixture drops below the profile of the 80% ternary mixture at approximately 6 mm (0.24 in.). The $\overline{y}_{2CT}$ values for the ternary mixtures are similar and are both smaller (more shallow) than those of the binary and control mixtures.

The mixtures with the lowest paste contents (20.5%) have the highest background chloride concentrations, possibly because, if the source of the chlorides is in the aggregate, then the higher aggregate content may increase the background chloride concentration. On the other hand, the background chloride concentration of the binary mixture is nearly the same as the ternary mixtures, so it may be the presence of mineral admixtures influencing the background chloride concentration.

The individual chloride profiles and the $\overline{y}_{2CT}$ for the concrete in set 6 are presented in Figs. B.28, B.39, B.30, B.32 and B.33 in Appendix B.

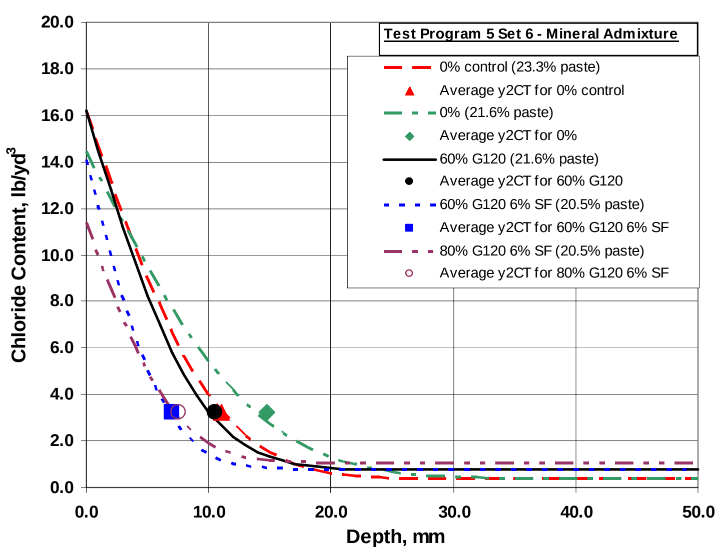


Fig. 3.76 Program 5 Set 6 Fick's profiles and $\overline{y}_{2CT}$ for concrete mixtures with paste contents ranging from 23.3% to 20.5% and containing G120 GGBFS or Silica Fume

The D_{eff} and $\overline{y}_{2CT}$ for set 6 are presented graphically in Figs. 3.77 and 3.78.

For the control mixtures, the reduction in paste content from 23.3% to 21.6% resulted in an (expected) increase in the D_{eff}, from 0.38 to 0.65 mm^2/day. The control mixture with 21.6% paste has the highest D_{eff} of the set, indicating the highest permeability.

Partial replacement of cement with 60% G120 GGBFS at a 21.6% paste content resulted in a statistically significant [$\alpha = 0.02$ (98%)] (Table 3.41a) decrease in the D_{eff} from 0.65 to 0.28 mm^2/day.

As discussed previously, the ternary mixtures have a lower paste content (20.5%) than the binary (21.6%) and control (23.3%) mixtures. The combined effect of including silica fume to make a ternary mix (60% G120 GGBFS and 6% SF) and reducing the paste content to 20.5% is lower permeability, as indicated by lower D_{eff} values. D_{eff} for the ternary mix containing 60% GGBFS and 6% SF is 0.14 mm^2/day, half of the value for the binary mixture containing 60% G120 GGBFS binary and less than 40% of the value for the 0% control mix. Similarly, the ternary mixture containing 80% G120 GGBFS and 6% SF also has a very low D_{eff} (0.18 mm^2/day). These differences are statistically significant, with the exception of the difference between the control mixture and the binary mixture containing 60% G120 GGBFS (Table 3.41a).

In general, the results indicate that any increase in permeability due to the reduced paste content in the ternary mixtures was compensated for by the addition of mineral admixtures, in particular 60% or 80% G120 GGBFS and 6% SF. It is not clear why the increase in GGBFS from 60% to 80% resulted in a slight but statistically significant increase in D_{eff}. A control mixture without mineral admixtures was not feasible at the 20.5% paste content due to lack of cohesion and workability at the reduced paste content. The addition of mineral admixtures provided the additional cohesion and workability necessary to achieve a cohesive, workable and placeable mix at the lower paste content.

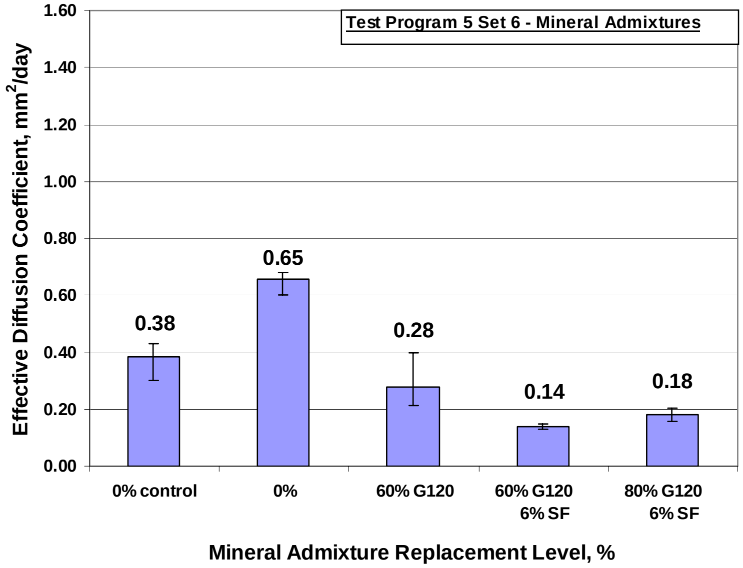


Fig. 3.77 Program 5 Set 6 Effective Diffusion Coefficients versus Mineral Admixture Replacement Level % for concrete mixtures with paste contents ranging from 23.3% to 20.5% and containing G120 GGBFS or Silica Fume

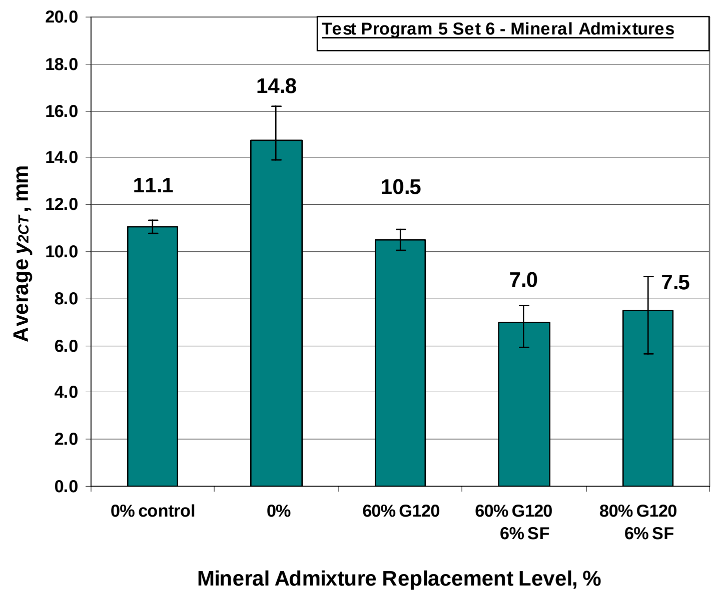


Fig. 3.78 Program 5 Set 6 $\overline{y}_{2CT}$ versus Mineral Admixture Replacement Level % for concrete mixtures with paste contents ranging from 23.3% to 20.5% and containing G120 GGBFS or Silica Fume

The results for $\overline{y}_{2CT}$ (Fig. 3.78) nearly mirror the D_{eff} results. The only exception is the difference between the $\overline{y}_{2CT}$ values for the two ternary mixtures were not statistically significant (Table 3.41b).

Table 3.41 Student's t-Test Results for Program 5 Set 6

(a) D_{eff}

	Replacement Level, %	D_{eff}	Replacement Level %G120-%SF				
			0-0 control	**0-0**	**60-0**	**60-6**	**80-6**
Replacement Level %G120-%SF	**0-0 control**	0.38		Y 0.01 (99%)	N	Y 0.01 (99%)	Y 0.01 (99%)
	0-0	0.65			Y 0.02 (98%)	Y 0.01 (99%)	Y 0.01 (99%)
	60-0	0.28				Y 0.10 (90%)	Y 0.17 (83%)
	60-6	0.14					Y 0.15 (85%)
	80-6	0.18					

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

(b) $\overline{y}_{2CT}$

	Replacement Level, %	$\overline{y}_{2CT}$, mm	Replacement Level %G120-%SF				
			0-0 control	**0-0**	**60-0**	**60-6**	**80-6**
Replacement Level %G120-%SF	**0-0 control**	11.1		Y 0.01 (99%)	N	Y 0.01 (99%)	Y 0.03 (97%)
	0-0	14.8			Y 0.03 (97%)	Y 0.01 (99%)	Y 0.01 (99%)
	60-0	10.5				Y 0.02 (98%)	Y 0.11 (89%)
	60-6	7.0					N
	80-6	7.5					

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

Overall, it is observed that for all mixtures in set 6, the addition of mineral admixtures resulted in decreases in permeability and chloride penetration. A reduction in the paste content for the mixtures with no mineral admixtures results in an increase in permeability, consistent with the results of Program 1. The replacement of cement with 60% G120 GGBFS, however, more than compensated for this increase in permeability. The ternary mixtures with 20.5% paste both had lower permeability than the binary mixture with 21.6% paste and the replacement of cement with 6% SF more than compensated for the permeability increase that might result from a reduction in paste content from 21.6% to 20.5%. Ternary mixtures with 60% and 80% G120 GGBFS and 6% SF at 20.5% paste content had significantly lower permeability than mixtures with no mineral admixtures and higher paste contents (23.3% or 21.6%). A slight increase in the D_{eff} and $\overline{y}_{2CT}$ was observed in the ternary mixture for an increase in the volume of cement replaced, from 60% to 80%, by G120 GGBFS.

3.13.6 Program 5 - Summary

Partial replacement of portland cement with either Grade 100 (G100) or 120 (G120) GGBFS is effective in reducing the permeability and chloride penetration into concrete; G100 GGBFS appears to be more effective than G120 GGBFS in binary concrete mixtures with equivalent paste contents and replacement levels.

The results indicate that for G120 GGBFS, a 60% replacement does not provide a statistically significant reduction in permeability compared with a 30% replacement level. The results do indicate, however, that a partial replacement of cement with 60% G120 GGBFS provides a statistically significant reduction in the permeability as compared to a mixture with the same paste content containing 100% portland cement.

In this program, the concrete containing 6% SF has a lower permeability than the concrete containing 3% SF. D_{eff} for the matching control mixture in this set appears to be lower than expected. As a result, the data do not show a statistically significant reduction in the concrete permeability for binary mixtures due to the use of SF.

The binary mixture with a paste content of 23.3% containing 60% G100 GGBFS shows reduced permeability compared to the control mixture (no GGBFS). The ternary mixture containing 60% G100 GGBFS and 6% SF has lower permeability than the control mixture (no mineral admixtures) and the binary mixture containing 60% G100 GGBFS.

The binary mixture with a paste content of 21.6% containing 60% G120 GGBFS shows reduced permeability compared to the control mixture. The ternary mixture containing 60% G120 GGBFS and 6% SF has a lower permeability than the control mixture.

Reduced paste contents are desirable to decrease free shrinkage and reduce cracking in bridge decks. Reducing paste content, however, can have an adverse effect on permeability, reducing the concrete's ability to resist chloride penetration. The role of reduced paste contents and optimized aggregate gradations for LC-HPC are discussed in detail by Lindquist et al. (2008) and McLeod (2005). Mineral admixtures can provide additional workability and cohesion to mixtures with reduced paste contents to maintain a placeable mix. In this study, mixtures with various (reduced) paste contents and replacement levels using mineral admixtures are compared to determine whether the use of mineral admixtures compensates for increased permeability caused by reduced the paste contents. The results indicate that binary and ternary mixtures with the lower paste content containing G120 GGBFS, SF, or both have lower permeabilities than mixtures containing no mineral admixtures at the higher paste contents. The mineral admixtures reduced the permeability sufficiently to compensate for any increase in permeability due to reduced paste content.

3.14 PROGRAM 6 – SHRINKAGE REDUCING ADMIXTURE

The use of a shrinkage reducing admixtures (SRA) in concrete has been shown to reduce free shrinkage and represents an possible method to reduce cracking for many applications, including bridge decks. There exists little information regarding the effect of SRAs on chloride penetration in long-term ponding tests. This Program represents a preliminary study to examine the effect of SRAs on permeability.

Program 6 includes two sets of concrete mixtures used to examine the effect of SRAs on the resistance to chloride penetration. Each set compares the performance of control mixtures without an SRA with concrete containing an SRA. The SRA dosage rates used in this study are 1% and 2% by weight of cement. The manufacturer's recommended dosage range of SRA is equivalent to 0.7% to 2.0% by weight of cement for an assumed mixture containing 365 kg/m^3 (615 lb/yd^3) of cement. The dosages used in this study are consistent with the manufacturer's recommendations.

The concrete in set 1 has 24.2% paste and a *w/c* ratio of 0.45. The control mixture was cured for 7 days, and the concrete containing the SRA was cured for both 7 and 14 days. The concrete in set 2 has 23.3% paste, a *w/c* ratio of 0.42, and was cured for 14 days. All of the concrete mixtures in Program 6 contain Type I/II cement. Additional Program 6 details are provided in Section 2.7.1. Mixture proportions, plastic concrete properties and compressive strengths are provided in Appendix A.

As discussed in Chapter 2, all of the concrete in this program is air entrained and intended to have adequate workability and cohesion for use in the field. One challenge in working with an SRA is achieving and maintaining a stable air void system, and maintaining the desired entrained air content represents the biggest challenge for implementing the use of SRAs in bridge deck concrete. For the mixtures in this program cast with SRA dosages of 2%, achieving and maintaining a stable, consistent, and repeatable air content was difficult, even in the carefully controlled laboratory environment. While the lab mixtures containing 2% SRA had adequate plastic properties for placement in the field (workability, cohesion, and finishability), there is some concern whether they could be produced in the field with satisfactory control over the air content. The air content of the concrete containing 1% SRA appeared to be more easily controlled. Therefore, it is likely that a 1% dosage rate (or lower) may be more successfully implemented in the field. It is recommended that any project with LC-HPC concrete specified to include an SRA be thoroughly field tested with multiple (more than two), back-to-back qualification batches meeting the specifications for air content, slump, concrete temperature, and haul time. Prior to construction and concrete placement in an LC-HPC bridge deck, it is essential to ensure adequate, repeatable adherence to LC-HPC concrete specifications for a concrete containing an SRA.

SRAs have a negative effect on the cohesiveness of concrete, limiting the potential for reducing the paste content below 23.3%. Thus the addition of silica fume to mixtures containing SRA may be one way to improve the cohesion and reduce the permeability of the mixtures.

Table 3.42 Program 6 – Summary

Set	Paste Content, %	*w/c*	Curing Period, days	SRA Dosage, %
1	24.2	0.45	7 7 14	0 2 2
2	23.3	0.42	14	0 1

A summary of Program 6 is provided in Table 3.42. Additional Program 6 details are provided in Section 2.7.1. Mixture proportions, plastic concrete properties and compressive strengths are provided in Appendix A. The results of program 6 are generally inconclusive about the effect of SRA on chloride penetration in concrete and further investigation is necessary.

3.14.1 Program 6 Sets 1 and 2 (2% and 1% SRA)

Set 1 includes mixtures containing 2% SRA and a *w/c* ratio of 0.45 (24.2% paste), while set 2 includes mixtures containing 1% SRA and *w/c* ratio of 0.42 (23.3% paste). All of the concrete in Program 6 contains 318 kg/m^3 (535 lb/yd^3) of Type I/II cement.

For the concrete in set 1, the Fick's profile for the concrete containing 2% SRA with 7 days curing has the highest surface concentration, but then drops below the profile of the control mixture (no SRA) at approximately 9 mm (0.35 in.), as shown in Fig. 3.79. The control mixture has the highest profile (by a small percent) for depths greater than approximately 9 mm (0.35 in.) and has the largest (deepest) $\overline{y}_{2CT}$, indicating the highest permeability for set 1. The profile of the concrete containing 2% SRA with 14 days of curing has the lowest profile and smallest $\overline{y}_{2CT}$, indicating that it has the lowest permeability for the set. The individual chloride profiles and the y_{2CT} depths for the concrete in set 1 are presented in Figs. B.3, B.6 and B.41 in Appendix B.

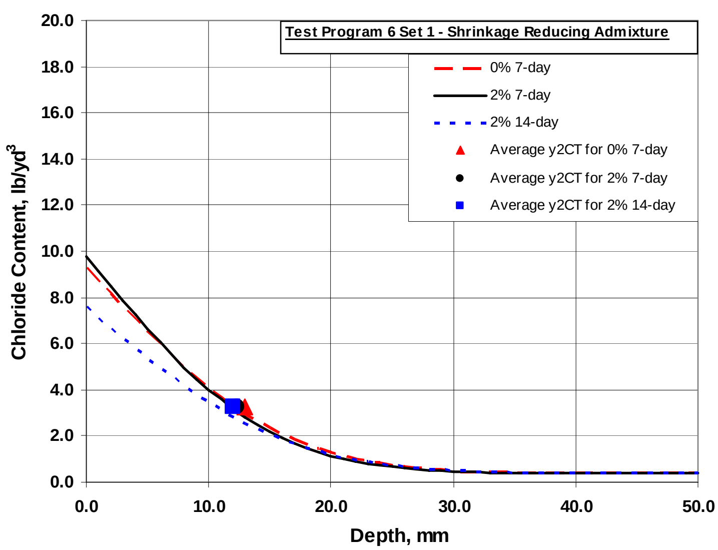


Fig. 3.79 Program 6 Set 1 Fick's profiles and $\overline{y}_{2CT}$ for concrete mixtures with 24.2% paste content, *w/c* ratio of 0.45 and containing up to 2% SRA

For the concrete in set 2 (14 days curing), the Fick's profile for the concrete containing 2% SRA has the lower surface concentration, the lower profile and smaller

$\overline{y}_{2CT}$, as shown in Fig. 3.80, indicating that it has the lower permeability for the set. The individual chloride profiles and the y_{2CT} depths for the concrete in set 2 are presented in Figs. B.28 and B.37 in Appendix B.

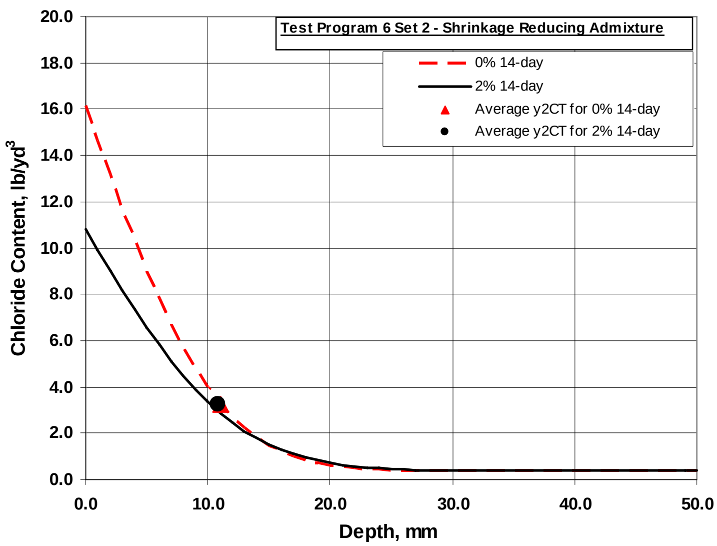


Fig. 3.80 Program 6 Set 2 Fick's profiles and $\overline{y}_{2CT}$ for concrete mixtures with 23.3% paste content, *w/c* ratio of 0.42 and containing up to 1% SRA

The D_{eff} and $\overline{y}_{2CT}$ for sets 1 and 2 are presented graphically in Figs. 3.81 and 3.82.

For set 1, the addition of 2% SRA for concrete cured for 7 days resulted in an a decrease in the D_{eff} from 0.84 to 0.73 mm^2/day and a decrease in $\overline{y}_{2CT}$ from 13.0 to 12.3 mm (0.51 to 0.48 in.). The decrease in the D_{eff} is statistically significant at α = 0.12 (88%) (Table 3.43), but the decrease in $\overline{y}_{2CT}$ is not statistically significant. For two batches cured for 7 days, both performance measures indicate that the addition of an SRA decreases the permeability. The concrete containing 2% SRA and cured for 14 days exhibits an increase in the D_{eff} from 0.73 to 0.89 mm^2/day (statistically significant) but a decrease in the $\overline{y}_{2CT}$ from 12.3 to 12.0 mm (0.48 to 0.47 in.), a difference which is not statistically significant (Table 3.43). The D_{eff} results for this mixture are not consistent with $\overline{y}_{2CT}$ and the Fick's profile, which indicate lower permeability. It is expected that additional curing should reduced the permeability of the concrete and subsequentially the D_{eff} values.

For set 2, the addition of 1% SRA resulted in an increase in the D_{eff} from 0.38 to 0.48 mm^2/day, but a decrease in the $\overline{y}_{2CT}$ from 11.1 to 10.8 mm (0.44 to 0.43 in.), neither of which were statistically significant differences (Table 3.44). The control for set 2 (0% SRA) also served as a control for Program 5 set 3 ("0% Control" in Section 3.13.3). Section 3.13.3 includes a discussion that the D_{eff} results for this control mixture ("0% SRA" in this set) may be lower than expected and not provide a reasonable basis for comparison. Therefore, if only the Fick's profile and $\overline{y}_{2CT}$ are considered for set 2, the results indicate that the concrete containing 1% SRA, has slightly lower chloride penetration than the control mixture, although the difference in $\overline{y}_{2CT}$ values is not statistically significant.

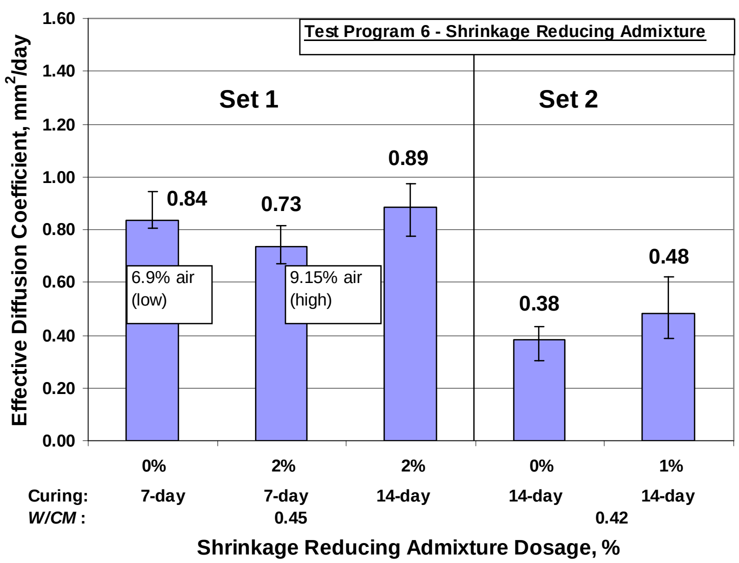


Fig. 3.81 Program 6 Sets 1 and 2 Effective Diffusion Coefficients versus Shrinkage Reducing Admixture Dosage for concrete mixtures containing SRA. Set 1 concrete has 24.2% paste content and a *w/c* ratio of 0.45. Set 2 concrete has 23.3% paste content and a *w/c* ratio of 0.42.

Overall for sets 1 and 2, the concrete containing SRA appears to have lower permeability than the control mixtures, but there is a lack of clarity in the results. It is recommended that this preliminary study be expanded to further examine the permeability of concretes containing SRA before strong conclusions are developed. Any future program should include control mixtures (0% SRA), as well as mixtures containing 1% SRA, and curing periods of both 7 and 14 days. Additional testing could also include smaller dosages of SRA and mixtures containing both SRA and silica fume to improve cohesion. Companion tests for free shrinkage and strength are also recommended.

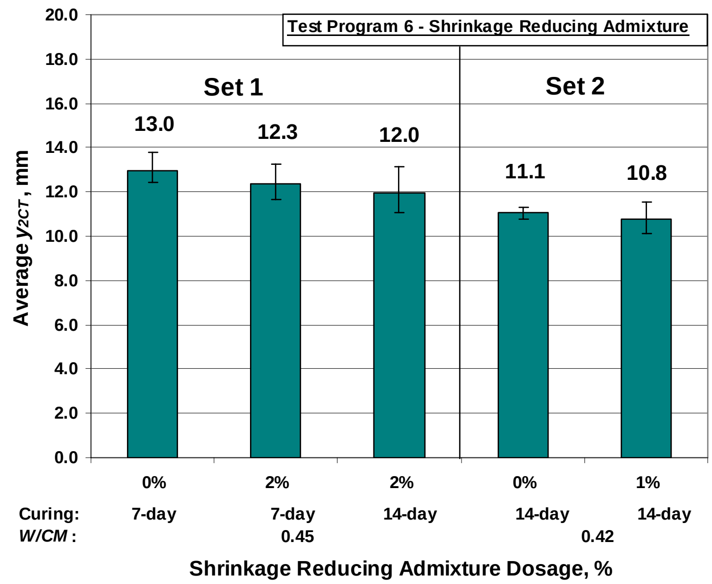


Fig. 3.82 Program 6 Sets 1 and 2 $\bar{y}_{2CT}$ versus Shrinkage Reducing Admixture Dosage for concrete mixtures containing SRA. Set 1 concrete has 24.2% paste content and a *w/c* ratio of 0.45. Set 2 concrete has 23.3% paste content and a *w/c* ratio of 0.42.

Table 3.43 Student's t-Test Results for Program 6 Set 1

	% - days	D_{eff}	SRA Dosage % - Curing Period, days			$\bar{y}_{2CT}$, mm	SRA Dosage % - Curing Period, days		
			0-7	2-7	2-14		0-7	2-7	2-14
SRA Dosage, %-Curing Period, days	0-7	0.84		Y 0.12 (88%)	N	13.0		N	N
	2-7	0.73			Y 0.12 (88%)	12.3			N
	2-14	0.89				12.0			

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

Table 3.44 Student's t-Test Results for Program 6 Set 2

	SRA, %	D_{eff}	SRA, %		$\bar{y}_{2CT}$, mm	SRA, %	
			0	**1**		**0**	**1**
SRA, %	**0**	0.38		N	11.1		N
	1	0.48			10.8		

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

3.15 PROGRAM 7 – STANDARD DOT BRIDGE DECK CONCRETE MIXTURES

Program 7 includes two sets comparing different standard department of transportation (DOT) bridge deck mixtures. The mixtures contain Type I/II portland cement and no mineral admixtures. The three mixtures in set 1 were cured for 7 days according to the standard curing practices of the Kansas DOT. The control mixture with 24.4% paste represents a standard LC-HPC bridge deck mix with a *w/c* ratio of 0.45 and a cement content of 318 kg/m^3 (535 lb/yd^3). A mixture with 26.9% paste represents the standard mix used for bridge subdecks in the State of Kansas and is called the "KDOT" mixture in this program. The mixture contains 358 kg/m^3 (602 lb/yd^3) of Type I/II portland cement and has a *w/c* ratio of 0.44. A mixture with 29.6% paste is a modified version of an older standard mix used on bridge decks in Missouri and is called the "MoDOT modified" mixture in this program. The mixture contains 433 kg/m^3 (729 lb/yd^3) of cement. This large cement content is generally recognized as having a negative effect on bridge deck cracking. It is important to note that the 29.6% mixture has a lower *w/c* ratio (0.37) and a lower air content (5%) than the two other mixtures.

For set 2, an LC-HCP control mixture with a *w/c* ratio of 0.42 and 23.3% paste is compared with the standard KDOT bridge subdeck mixture. Both mixtures are cured for the LC-HPC recommended 14-day curing period. The control mixtures for both sets have an optimized aggregate gradation (discussed in Sections 2.6 and 2.7), whereas the KDOT and MoDOT modified mixtures do not.

A summary of Program 7 is provided in Table 3.45. Additional Program 7 details are provided in Section 2.7.1. Mixture proportions, plastic concrete properties, and compressive strengths are provided in Appendix A.

Table 3.45 Program 7 – Summary

Set	Paste Content, %	*w/c*	Curing Period, days	Design Air Content, %
1	24.2 - control	0.45	7	8
	26.9	0.44		6
	29.6	0.37		5
2	23.3 – control	0.42	14	8
	26.9	0.44		6.5

In general, the results for both sets indicate that the LC-HPC control mixtures have lower permeability than the KDOT mixtures. The MoDOT modified mixture exhibits the lowest permeability for set 1 (7-day cure), presumably because of the low *w/c* ratio and air content.

3.15.1 Program 7 Sets 1 and 2 (Standard DOT Bridge Deck Mixtures)

For the concrete in set 1, the Fick's profile for the KDOT mix is higher than the LC-HPC control mix throughout the depth, indicating that the KDOT mix has higher permeability, as shown in Fig. 3.83. The MoDOT modified mix has the highest surface concentration, then dips below the KDOT mix at approximately 6 mm (0.24 in.) and below the LC-HPC mix at approximately 13 mm (0.51 in.). For depths greater than 13 mm (0.51 in.), the modified MoDOT mix appears to have the lowest permeability in set 1. The $\overline{y}_{2CT}$ values for the LC-HPC and MoDOT mixes are nearly identical. $\overline{y}_{2CT}$ for the KDOT mix is the greatest (deepest) for set 1, indicating the most chloride penetration.

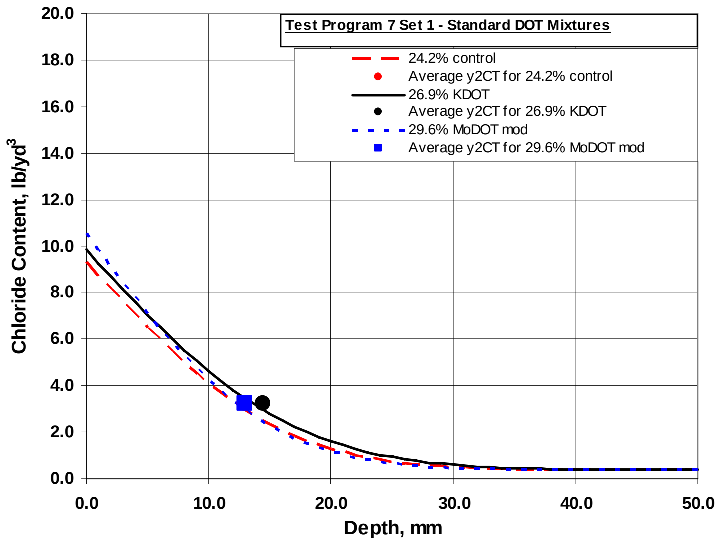


Fig. 3.83 Program 7 Set 1 Fick's profiles and $\bar{y}_{2CT}$ for standard bridge deck concrete mixtures

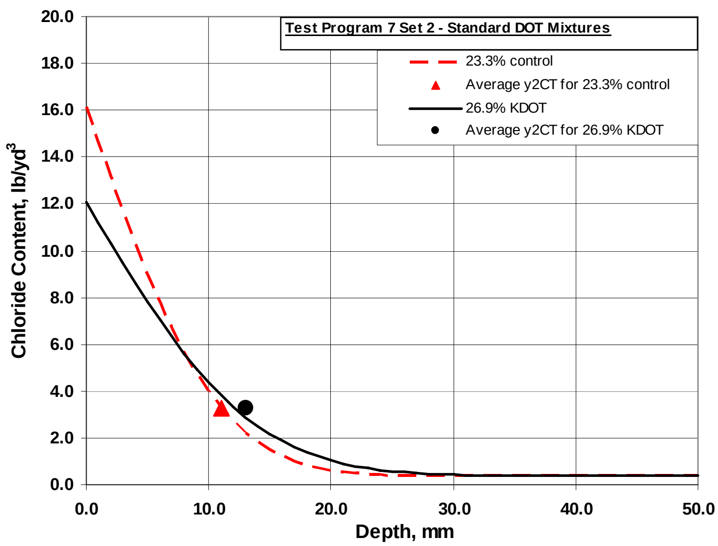


Fig. 3.84 Program 7 Set 2 Fick's profiles and $\bar{y}_{2CT}$ for standard bridge deck concrete mixtures

For set 2, the Fick's profile for the LC-HPC mixture has the highest surface concentration and then drops below the KDOT mix at approximately 8 mm (0.31 in.), as shown in Fig. 3.84, indicating lower permeability for the depths greater than 8 mm

(0.31 in.). $\overline{y}_{2CT}$ of the KDOT mix is greater (deeper) than for the LC-HPC control mix, indicating greater chloride penetration.

The individual chloride profiles and the y_{2CT} for the concrete in set 1 are presented in Figs. B.3, B.1 and B.2, and for the concrete in set 2 in Figs. B.28 and B.38 in Appendix B.

The D_{eff} and $\overline{y}_{2CT}$ for sets 1 and 2 are presented graphically in Figs. 3.85 and 3.86.

For concretes in set 1, all of which were cured for 7 days, the LC-HPC control mixture with 24.2% paste has a lower D_{eff} (0.84 mm^2/day) than the KDOT mixture with 26.9% paste (D_{eff} = 0.96 mm^2/day). The MoDOT modified mix with 29.6% paste has a D_{eff} of 0.71 mm^2/day. The differences between these mixtures are all statistically significant (Table 3.46). The fact that the MoDOT modified mix with 29.6% paste has the lowest permeability of set 1 is probably due to the low *w/c* ratio and low air content. Contrary to expectations, the KDOT mix has the highest permeability, higher than the LC-HPC control mixture. The KDOT mix has a higher paste content, a lower *w/c* ratio, and a lower air content than the LC-HPC mix, which indicate that the opposite should be true.

The $\overline{y}_{2CT}$ results are consistent with the D_{eff} results, also indicating that the KDOT mix has the highest chloride penetration for the set. The results for $\overline{y}_{2CT}$ are all statistically significant at α = 0.02 (98%) or lower (Table 3.46). $\overline{y}_{2CT}$ for the LC-HPC control mix and the MoDOT modified mixture are identical. For set 1, D_{eff}, $\overline{y}_{2CT}$, and the Fick's profiles indicate that the KDOT mix is more permeable than the LC-HPC mix.

For the concretes in set 2, the trends are similar to the concretes in set 1. The D_{eff} of the KDOT mixture is 0.62 mm^2/day and the D_{eff} of the LC-HPC mixture is 0.38 mm^2/day. $\overline{y}_{2CT}$ for the KDOT mix is 13.1 mm (0.52 in.), also higher than the LC-HPC mixture, 11.1 mm (0.44 in.), indicating that the KDOT mix has greater chloride penetration than the LC-HPC control mix. For set 2, the differences in D_{eff}

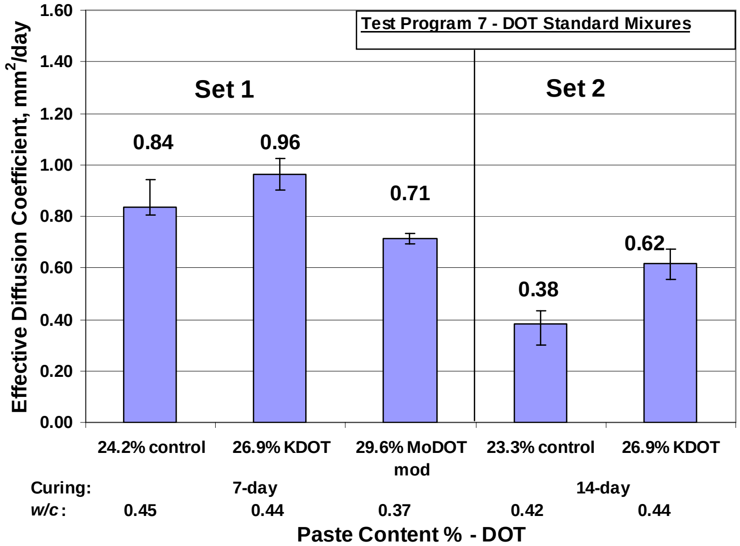


Fig. 3.85 Program 7 Sets 1 and 2 Effective Diffusion Coefficients versus Paste Content and DOT mixture for standard bridge deck concrete mixtures

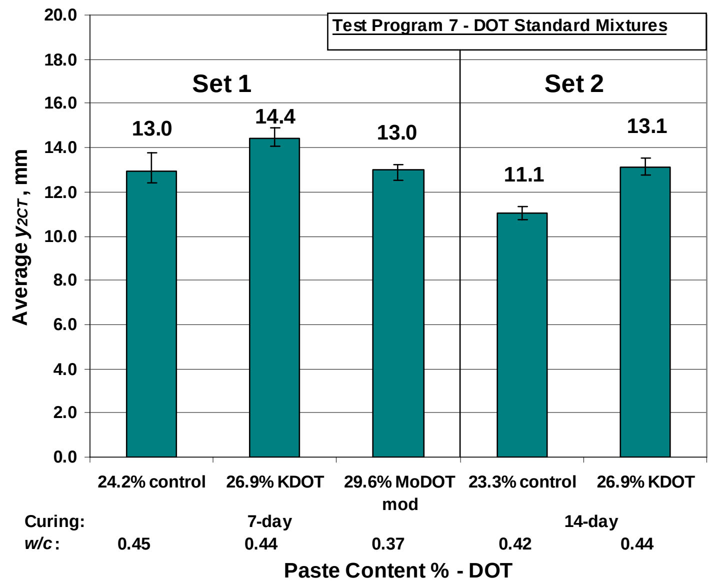


Fig. 3.86 Program 7 Sets 1 and 2 $\overline{y}_{2CT}$ versus Paste Content and DOT mixture for standard bridge deck concrete mixtures

and $\overline{y}_{2CT}$ are statistically significant at α = 0.02 (98%) and α = 0.01 (99%) (Table 3.47), respectively.

Overall, the results of sets 1 and 2 indicate that the KDOT mixtures have higher permeability and chloride penetration than the LC-HPC control mixtures. In set 1, the MoDOT mix has the lowest permeability due to the low *w/c* ratio and air content.

Table 3.46 Student's t-Test Results for Program 7 Set 1

	Paste Content %	D_{eff}	Paste Content, %			$\bar{y}_{2CT}$, mm	Paste Content, %		
			24.2	26.9	29.6		24.2	26.9	29.6
Paste Content, %	24.2	0.84		Y 0.14 (86%)	Y 0.03 (97%)	13.0		Y 0.05 (95%)	N
	26.9	0.96			Y 0.01 (99%)	14.4			Y 0.02 (98%)
	29.6	0.71				13.0			

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

Table 3.47 Student's t-Test Results for Program 7 Set 2

	Paste Content, %	D_{eff}	Paste Content, %		$\bar{y}_{2CT}$, mm	Paste Content, %	
			23.3	26.9		23.3	26.9
Paste Content, %	23.3	0.38		Y 0.02 (98%)	11.1		Y 0.01 (99%)
	26.9	0.62			13.1		

Note: See the Table 3.7 note for an explanation of the terms "N," and "Y α (CI)."

3.15.2 Program 7 - Summary

Overall, the results of Program 7 indicate that the KDOT mixtures have higher permeability and chloride penetration than the LC-HPC control mixtures. This was not expected because the KDOT mixtures have a higher paste content, and a lower *w/c* ratio and air content than the LC-HPC control mixtures, all of which indicate that the opposite should be true. In set 1, the MoDOT mix has the lowest permeability due to the low *w/c* ratio and air content.

The LC-HCP control mixtures cannot be compared between sets due to differences in the *w/c* ratio and paste contents. The KDOT mixtures in sets 1 and 2 cannot be compared to each other because of differences in the design air content.

Chapter 4

LOW-CRACKING HIGH-PERFORMANCE CONCRETE (LC-HPC) AND CONTROL BRIDGE DECK CONSTRUCTION SPECIFICATIONS AND BRIDGES

4.1 GENERAL

This chapter describes the development and specifications for the first 14 Low-Cracking High-Performance Concrete (LC-HPC) bridge decks in Kansas. The chapter is divided into three sections covering (1) the specifications and methods for control bridge decks, (2) the specifications and methods for LC-HPC bridge decks, and (3) details for the bridges in this study. The descriptions of the specifications for the LC-HPC bridge decks presented in this chapter are primarily focused on the construction methods and experiences, with an overview of the materials specifications. A complete discussion of the LC-HPC materials and production is presented by Lindquist et al. (2008).

The performance of the LC-HPC bridge decks is evaluated based on comparison with *control* bridge decks. The control bridge decks are similar to the LC-HPC decks in design, location, and date of construction, but the methods and materials used for these decks represent the typical non-low-cracking high-performance deck built in Kansas. The control decks generally consist of a conventional subdeck with a thin overlay containing 7% silica fume, designed to resist penetration of chlorides. Two of the 12 control decks included in this study are monolithic. The performance of the LC-HPC and control decks is described in Chapter 5.

In this chapter, the Kansas Department of Transportation (KDOT) standard methods and specifications used for the construction of the control bridges, most with silica fume overlay (SFO) decks, are outlined in Section 4.2. The LC-HPC bridge decks in Kansas are constructed in accordance with these standard KDOT specifications, supplemented by special provisions for aggregates, concrete, and construction. As the project has progressed, the special provisions have been modified, as described Section 4.3, which covers six versions of the aggregate special provision and seven versions of the concrete and construction special provisions.

The 14 LC-HPC bridge decks are denoted as LC-HPC-1 through LC-HPC-14. The eleven corresponding control decks are denoted as Control-1/2 through Control-13, with two of the control decks serving as controls for two of the LC-HPC decks. An additional alternate control deck, Control-Alt, is included in the study for a total of 12 control decks. A detailed description of each bridge deck is included in this study, including the design, location, and any special conditions, is provided in Section 4.4. The experiences and lessons learned with the construction of the 14 LC-HPC bridge decks and the 12 control decks are presented in Chapter 5. Chapter 5 also includes recommendations for future implementation of LC-HPC construction.

4.2 METHODS AND SPECIFICATIONS FOR CONTROL BRIDGE DECKS

Cracking in the LC-HPC bridge decks constructed in this project is compared with cracking in bridge decks constructed with conventional procedures, referred to as control bridge decks. The control decks were constructed in accordance with the 1990 version of the standard Kansas DOT specifications with some special provisions for concrete and silica fume overlays (SFO). The applicable concrete and SFO special provision numbers are listed in Table 4.1. The “-R” in each designation refers to the revision number for that special provision. The parameters of interest for the bridge designs and for the aggregate, concrete, and construction specifications are described.

Table 4.1 – Control Bridge Specifications – Special Provision Designations

Control Bridge Number	Concrete Specification	Concrete Grade	Overlay Specification	Project Addendum?
Control 1/2	90M-156-R5	GR 30 (GR 4.4) AE SA	90M-158-R10	No
Control 3	90M-156-R7	GR 31 (GR 4.5) AE SA	90M-158-R10	Yes
Control 4	90M-156-R7	GR 31 (GR 4.5) AE SA	90M-158-R10	Yes
Control 5	90M-156-R7	GR 31 (GR 4.5) AE SA	90M-158-R10	Yes
Control 6	90M-156-R7	GR 31 (GR 4.5) AE SA	90M-158-R10	Yes
Control 7	90M-156-R7	GR 31 (GR 4.5) AE SA	90M-158-R10	Yes
Control 8/10†	90M-156-R8	GR 31 (GR 4.5) AE SA	NA†	No
Control 9	90M-156-R8	GR 31 (GR 4.5) AE SA	90M-158-R10	Yes
Control 11	90M-156-R5	GR 30 (GR 4.4) AE SA	90M-158-R10	Yes
Control 12	90M-156-R8	GR 28 (GR 4.0) AE SA	90M-158-R8	Yes
Control 13	90M-156-R9	GR 31 (GR 4.5) AE SA	90M-158-R11	Yes
Control Alt†	90M-156-R5	GR 30 (GR 4.4) AE SA	NA†	No

† Monolithic deck.

4.2.1 Design

Control bridges are similar in structural design to the matching LC-HPC bridges. They are, in most cases, steel girder bridges with limited skews, located close to and similar in age to the LC-HPC bridges. Sister bridges were chosen, when available, for the greatest consistency in design and contractor methods. Also, the standard KDOT high performance deck system, with a Silica Fume Overlay (SFO), was the deck type used for most of the control bridges. SFO bridge decks built in Kansas generally consist of a 180 mm (7 in.) subdeck, with a 40 mm (1.6 in.) overlay containing 7% silica fume by weight. The system provides 75 mm (3 in.) of cover over the top mat of reinforcing steel. The bottom cover is typically 30 mm (1.2 in.). Two of the control decks (Control 8/10 and Control Alt) were monolithic and bridge Control 8/10 had prestressed girders.

4.2.2 Concrete

Separate special provisions are used for the concrete in the subdeck and monolithic decks and for the concrete in the silica fume overlays.

The concrete special provisions cover a wide range of applications and required compressive strengths. The control bridge subdecks and monolithic decks in this study were constructed with three grades of concrete: Grades 28, 30 and 31 (Grades 4.0, 4.4 and 4.5). In version 90M-156–R7 and all subsequent versions of the concrete special provision, Grade 30 (Grade 4.4) was renamed to Grade 31 (Grade 4.5), but the specification requirements remained identical. The concrete typically used in a Kansas subdeck is also used in monolithic deck construction. It contains a minimum cement content of 357 kg/m^3 (602 lb/yd^3) and a total air content of 6.5±1.5%. Class F fly ash was used in Control 3, 4, 5, 6 and 7 at a rate of 79 kg/m^3 (133 lb/yd^3) or approximately 23% by volume. The total cementitious materials content and paste content was higher than used in the other subdecks, with 397 kg/m^3 (669 lb/yd^3) of total cementitious material and 29.0% paste. Mix design details for the control decks are reported by Lindquist et al. (2008). Grade 28 (Grade 4.0) concrete has a maximum *w/c* ratio of 0.44, while the maximum *w/c* ratio for Grades 30 and 31 (Grades 4.4 and 4.5) is 0.40. The maximum allowable slump for concrete with water reducers is 175 mm (7 in.) or 75 mm (3 in.) for bridge decks and subdecks that do not contain water reducing admixtures.

The silica fume overlay special provisions require a minimum cement content of 346 kg/m^3 (581 lb/yd^3) and a minimum silica fume content of 26 kg/m^3 (44 lb/yd^3). The maximum *w/cm* ratio is 0.37 and the required air content is 6.5 ± 1.5%. The target slump is 50 to 125 mm (2 to 5 in.) with a 25% tolerance or 19 mm (3/4 in.) (whichever is greater) deviation allowed. The ratio of coarse aggregate to fine aggregate is 1:1 by mass, and the nominal maximum sized aggregate (MSA) is 12.5 mm (½ in.).

4.2.3 Aggregates

The requirements for the aggregate in bridge decks, subdecks, and overlays include requirements for durability which are discussed in detail by Lindquist et al. (2008). The maximum absorption for coarse aggregates used in bridge decks is 2.0%. The coarse aggregate predominantly used in bridge decks in Kansas is Kansas limestone that has been approved for durability by laboratory testing. The gradation requirements for coarse aggregate used in bridge decks allows a maximum size aggregate with material retained on the 12.5-mm (1/2-in.), 19.0-mm (3/4-in.), or even the 25.0-mm (1-in.) sieve. The Kansas City Metro Materials Board limits the maximum absorption to 0.5%, necessitating the use of imported aggregates, typically granite or quartzite. The City of Overland Park, Kansas requires the coarse aggregate to be granite, with a maximum absorption of 0.5% and an average specific gravity of 2.62.

The fine aggregates used in Kansas are predominantly river sands. The materials are slightly reactive, so there can be alkali-silica reaction (ASR) problems when concrete mixtures contain high quantities of the sand. Kansas River Sand in the northeast portion of the state typically has a specific gravity of 2.62 and an absorption of 0.7%.

The specified combination of coarse aggregate and fine aggregate is 50:50 ratio by weight of aggregate. Details about the durability requirements for the aggregates and the combined aggregates are discussed by Lindquist et al. (2008).

Some bridges have additional *project specific specifications* that tighten the special provision requirements to comply with the local municipality. Five of the control bridges, Control 3 through Control 7, have an additional project specific aggregate specification, 90M-7218 that requires the coarse aggregate to meet the Kansas City Metro Materials Board requirements. The maximum allowable absorption for the coarse aggregate in these decks is 0.7%, rather than the KDOT standard 2.0%. These bridges, therefore, contain granite as the coarse aggregate instead of the KDOT Class 1 limestone.

4.2.4 Construction

The construction requirements for the control bridges are defined in the 1990 KDOT Standard Specification, Section 701 Concrete Structure Construction, with additional requirements outlined in the applicable versions of Special Provisions 90M(P)-91 Concrete Structure Construction (Section 701), 90M(P)-156 Concrete (Section 402), and 90M(P)-158 Silica Fume Overlay (Section 700).

Concrete Temperature Control

The KDOT specifications generally focus on the ambient air temperature, but have some provisions for the concrete temperature during hot or cold weather.

The KDOT concrete special provisions provide limitations on the time between mixing and placement, based on the ambient air temperature. These limitations are outlined in Table 4.2. Concrete temperature is also considered, but only when the concrete temperature is greater than 32ºC (90ºF); then the concrete must be placed within 45 minutes.

Table 4.2 – Maximum Concrete Placement Time Based on Ambient Air Temperature

Ambient Air Temperature, T °C (°F)[†]	Maximum Concrete Placement Time (hours)	Set Retarder
T < 24° (75°)	1.5	No
24° (75°) ≤ T < 32° (90°)	1	No
24° (75°) ≤ T < 32° (90°)	1.5	Yes
T ≥ 32° (90°)	1	No

The Engineer may allow concrete to be placed during cold weather conditions, which are defined as occurring when the descending air temperature reaches 4ºC (40ºF) and until the ascending air temperature reaches 2ºC (35ºF). If concrete is placed during cold weather, the concrete temperature must be between 10º and 32ºC

(50º and 90ºF) at the time of placement. Concrete may not be placed if the air temperature is below -2ºC (20ºF).

For silica fume overlay (SFO) construction, concrete may not be placed when the descending air temperature in the shade and away from artificial heat reaches 7ºC (45ºF) or if the nighttime temperature after placement is expected to fall below 2ºC (35ºF). SFO concrete placement may not resume until ascending air temperatures reach 5ºC (40ºF).

Control of Evaporation Rate

Placement of concrete is not allowed when the environmental conditions are such that the evaporation rate equals or exceeds 1.0 kg/m^2/hr (0.2 lb/ft^2/hr). Environmental conditions affecting the evaporation rate (air temperature, wind speed, relative humidity) must be measured, recorded, and the evaporation rate estimated at least once per hour. (The concrete temperature is measured when the plastic concrete is tested for slump and air content.) If conditions cause the evaporation rate to exceed the limit, the contractor may proceed with placement if protective measures, such as fogging, wind breaks, and concrete cooling, are taken to maintain evaporation below 1.0 kg/m^2/hr (0.2 lb/ft^2/hr). This is the same as for LC-HPC decks except that for LC-HPC decks fogging may not be counted in the evaporation rate determination for LC-HPC decks.

Placement

The method of placement (pumping, conveyor belt, buckets, etc.) is not restricted.

Consolidation

Consolidation using vertically mounted internal gang vibrators is required for full-depth decks and subdecks. The standard KDOT specifications require that internal type (spud or tube) vibrators of the same type and size be mounted on a mechanical device with a maximum spacing of 300 mm (12 in.), as shown in Figure 5.1. The vibrator heads must have a diameter between 44 to 64 mm (1¾ to 2½ in.), a frequency of vibration between 8000 to 12000 vibrations per minute, an average amplitude between 0.635 to 1.27 mm (0.025 to 0.050 in.), and a minimum radius of action of 178 mm (7 in.).

The vibrators must be mounted so that they enter the concrete in a vertical position under the influence of their own weight, with enough flexibility to work themselves around the reinforcement. The mechanical device is mounted on either the finishing equipment or on an independent framework pulled along the grade rails. The gang vibrators must be inserted a maximum spacing of 300 mm (12 in.) spacing. A uniform time of vibration of 3 to 15 seconds should be ensured with timed controls (buzzer, light, automatic control). The vibrators should be extracted at a rate that will avoid voids or holes in the concrete. Vibrators may not be dragged horizontally through the concrete. Hand-held vibrators must be used in inaccessible and confined areas.

Figure 4.1 Vertically mounted internal gang vibrators.

Consolidation for SFOs is important in achieving a good bond with the subdeck. Consolidation is performed with a mechanical finishing screed, which is used to strike-off and consolidate the overlay to a minimum of 98% of the vibrated unit weight of the overlay material. Hand tamping with a 150×150 mm (6×6 in.) metal plate device is required for areas where the finishing screed does not reach.

Finishing

For subdecks and full-depth decks, strike-off is obtained with approved deck finishing equipment, commonly a double-drum roller screed in Kansas. For a SFO, strike-off is performed concurrently with the consolidation operation, using the same mechanical finishing screed described previously. Subdecks are to be left with an acceptable float or machine pan finish. For full-depth decks and SFOs, a tight, uniform surface should be achieved with the finishing equipment, then the final surface texture is produced, as described next.

Surface Texturing

For full-depth decks and SFOs, a textured surface finish is placed on the concrete surface by tining before concrete has set. Transverse grooves are produced with a tining float, having a single row of fins, to achieve 5-mm (3/16-in.) wide grooves that are 3-mm (1/8-in.) deep at 20-mm (¾-in.) centers. The operation is performed to achieve the desired texture, but should minimize the dislocation of coarse aggregate particles.

Fogging

Fogging is required for all subdecks and overlays, and is to begin immediately after the tining operation for placements with a textured driving surface, or after finishing for subdecks. The surface of the finished concrete should be maintained in a damp condition, with a "gloss to semi-gloss water sheen," until wet burlap is placed. Fogging should be applied over the entire placement width and reduced only if excess water accumulates on the surface. Fogging equipment should use pressure to produce a fine fog spray to keep a large surface area damp without depositing excess water.

Curing

The standard KDOT specifications require that full-depth bridge decks and overlays be initially cured with a liquid curing membrane. One coat must be applied to full-depth placements, while two coats, applied at right angles, must be applied to overlays. A liquid curing membrane is not allowed for subdecks. For full-depth bridge decks and SFOs, a liquid membrane meeting the requirements of Section 1400 of the KDOT Standard Specifications (Section 1405.2 a), is applied immediately after the tining float. The liquid membrane is required to comply with AASHTO M 148 for Type 1-D clear or translucent with fugitive dye compound. This liquid membrane acts as a pre-cure evaporation retarder until the wet burlap is placed. The purpose is to help prevent plastic shrinkage cracking. Wet burlap is applied and covered with white polyethylene sheeting once the concrete has hardened sufficiently to preclude marring of the surface. The burlap must be kept continuously wet for 7 days for subdecks, full-depth decks, and SFOs. For the first 24 hours of the 7-curing period, the polyethylene sheeting cannot be used during daylight hours if the concrete surface temperature is above 32ºC (90ºF).

Cold Weather Curing

When concrete is placed and the air temperature is expected to drop below 4.4ºC (40ºF) during the curing period, protective materials such as straw, additional burlap, blanketing materials and/or housing with artificial heat should be applied to maintain the concrete temperature between 4.4ºC (40ºF) and 32ºC (90ºF) as measured on the surface of the concrete.

4.3 METHODS AND SPECIFICATIONS FOR LC-HPC BRIDGE DECKS

This section presents a description of the methods and specifications used for the construction of LC-HPC bridge decks, and also documents the reasoning for each requirement. Changes to the specifications, as reflected in the multiple versions of the special provisions, are the result of experience gained during the construction of the decks. As a result, the specifications have continued to evolve, reflecting best practices in concrete materials and construction practices with the goal of minimizing cracking in bridge decks. This highlights a significant strength of the first phase of this study – the large scope, including the construction of 14 full-scale bridge decks in Kansas alone, has allowed for ongoing refinement of methods and specifications. As a result, considerable progress has been achieved over a relatively short period of time (5 to 6 years) and the repeatability of the methods and the outcomes (reduced cracking) has been demonstrated. The Special Provision numbers for the six versions of the aggregate specification, the seven versions of the concrete specification, and the seven versions of the construction specification, along with the corresponding LC-HPC bridge decks, and the versions of the specifications that are recommended for the second phase of this study are provided in Table 4.3. The special provisions are provided in Appendix C.

An addendum to the contract containing bridges LC-HPC-8, 9, and 10 was issued (K7891 Addendum) and is considered an integral part of the second version of the aggregate special provision 90M-7326 and the construction special provision 90M-7296. The addendum did not affect the concrete special provision 90M-7295. Special provisions LCHPC-1, 2, and 3 were written for bridge LC-HPC-14 which is located in the City of Overland Park, Kansas, and include additional requirements added by the city engineers.

The design requirements for LC-HPC bridge decks built in Kansas are described in Section 4.3.1. The requirements for aggregates, concrete, and construction, as required by the special provisions, are described in Sections 4.3.2

through 4.3.4. Changes to the special provisions in the various versions are discussed.

Table 4.3 – LC-HPC Specifications – Special Provision Designations

LC-HPC Bridge Number	Concrete Specification	Aggregate Specification	Construction Specification
1	90M-7181	90M-7182	90M-7190
2	90M-7181	90M-7182	90M-7190
3	90M-7275	90M-7182	90M-7276
4	90M-7275	90M-7182	90M-7276
5	90M-7275	90M-7182	90M-7276
6	90M-7275	90M-7182	90M-7276
7	90M-7275	90M-7182	90M-7276
8	90M-7295	90M-7326/ K7891 Addendum	90M-7296/ K7891 Addendum
9	90M-7295	90M-7326/ K7891 Addendum	90M-7296/ K7891 Addendum
10	90M-7295	90M-7326/ K7891 Addendum	90M-7296/ K7891 Addendum
11	90M-7338	90M-7339	90M-7332
12	90P-5095	90P-5085	90M-5097
13	90M-7360	90M-7359	90M-7361
14[†]	LCHPC-1	LCHPC-2	LCHPC-3
Phase 2	07-LC-HPC-Conc	07-LC-HPC-Agg	07-LC-HPC-Const

[†]LC-HPC-14 is a City of Overland Park, KS project.

4.3.1 Design

The LC-HPC and control bridge decks in this study are cast on composite steel girder bridges with minimal skew and integral abutments, with the exception of LC-HPC-8 , LC-HPC-10, and Control-8/10, which are composite prestressed girder bridges. The bridges had either jersey or corral rail barriers. The minimum required design compressive strength for the control bridge decks was either 28 or 31 MPa

(4000 or 4500 psi), while the required strength for the LC-HPC bridge decks was typically 24 MPa (3500 psi) and 28 MPa (4000 psi) for one deck. The only design change required for LC-HPC decks is the bottom cover is increased to 38.0 mm (1½ in.) due to the increase in the maximum size aggregate (MSA) from 19 to 25 mm (¾ to 1 in.).

4.3.2 Concrete

Seven versions of the "Low Cracking High Performance – Concrete" special provision to the KDOT 1990 Standard Specification exist. Special provision 90M-7181 was the first concrete specification for LC-HPC bridge decks (LC-HPC-1 and 2) and covers the first two LC-HPC bridge decks, which were let in a single contract. Special provision 90M-7275 was the second concrete specification for LC-HPC bridge decks (LC-HPC-3 through 7) and covers five LC-HPC bridge decks, which were let in two contracts. Special provision 90M-7295 was the third version of the concrete specification, covering three LC-HPC bridge decks let in one contract (LC-HPC-8, 9, and 10). Special provision 90M-7338 was the fourth version of the concrete specification, covering one LC-HPC bridge deck (LC-HPC-11). Special provision 90P-5095 was the fifth version of the concrete specification, covering one LC-HPC bridge deck (LC-HPC-12). Special provision 90M-7360 was the sixth version of the concrete specification, covering one LC-HPC bridge deck (LC-HPC-13). Special provision LCHPC-1 "Low Cracking High Performance Concrete Specification" was the seventh version of the concrete specification, covering one LC-HPC bridge deck (LC-HPC-14) located in Overland Park, Kansas, and reflects changes required by the city engineer.

The special provisions for concrete include requirements for the mix design, concrete testing, procedures for mixing, delivery and placement of LC-HPC concrete, and for a field qualification batch.

Mix Design

Concrete mix design requirements are outlined in the LC-HPC Concrete special provision. The initial concrete special provision, 90M-7181 (LC-HPC-1 and 2), required a compressive strength of 24 MPa (3500 psi) at 28 days, a maximum *w/c* ratio of 0.45, total air content of 8.0 ± 1.5%, and a cement content range of 310 to 334 kg/m^3 (522 to 563 lb/yd^3). In all versions, the design slump range is 36 to 75 mm (1½ to 3 in.), with a maximum allowable slump of 100 mm (4 in.). There are no substantial changes to the mix design in the second version of the special provision, 90M-7275 (LC-HPC-3 through 7). The third version of the special provision, 90M-7295, beginning with LC-HPC-8, and all subsequent versions reduce the required cement content range to 300 to 317 kg/m^3 (500 to 535 lb/yd^3) and the maximum *w/c* ratio to 0.42. The values for the cement content and *w/c* ratio were modified slightly, usually tightened, from those required in the special provisions for some of the LC-HPC decks. The modifications were due to lessons learned from experiences with previous LC-HPC deck construction, and to a lesser extent, from the information gained from the laboratory results. The recommended Phase 2 specifications require a compressive strength of 24 MPa (3500 psi) at 28 days, allow a *w/c* ratio range from 0.44 to 0.45, design total air content of 8.0 ± 1.0% with allowable values between 6.5% and 9.5%, a cement content range of 300 to 320 kg/m^3 (500 to 540 lb/yd^3), and a design slump range from 36 to 75 mm (1½ to 3 in.), with a maximum allowable slump of 90 mm (3½ in.).

For each bridge deck, an overview of the concrete requirements and properties and the modifications to the specification, if any, is provided in the discussion of experiences sections for each bridge (Chapter 5). Material details and a description of the experiences with production of LC-HPC are provided in Lindquist et al. (2008).

The volume of water and cement is required to be less than 27% of the total volume of the mix but this requirement is automatically satisfied by the specified cement contents and *w/c* ratios. Mineral admixtures are not permitted in LC-HPC concrete. Plasticizing admixtures are allowed. Slump control in the field may be accomplished by redosing with up to 50% of the original dose of the plasticizing admixture. The Engineer may otherwise allow up to 10 L/m^3 (2 gallons/yd^3) of water to be withheld from the mixture at the batch site and, if needed, added to the truck at the construction site to adjust the slump to comply with the specifications. Because of excessively high strengths that in some cases resulted from withholding water, this requirement was later modified in the field to require that all water be added at the plant. All concrete mix designs are submitted to the Engineer and the Research Development Engineer for review and approval prior to placement of any concrete or qualification batch.

The fifth version of the special provision, 90M-5095, beginning with LC-HPC-12, and all subsequent versions prohibit the use of set retarding or accelerating admixtures (Types B, C, D, E, and G). Previous versions of the concrete special provisions did not prohibit the use of these admixtures.

The seventh version of the special provision, LCHPC-1 (LC-HPC-14) increased the 28-day strength of the concrete to 28 MPa (4000 psi). This change was instituted for this particular letting at the request of the bridge design engineer because the deck had already been designed for a compressive strength of 28 MPa (4000 psi) when the decision was made to construct an LC-HPC deck. This did not, however, necessitate a change in the concrete mixture proportions. As described earlier, the Phase 2 recommended specifications continue to require a 28-day strength of 24 MPa (3500 psi).

<u>Concrete Temperature Control</u>

Temperature control of the plastic concrete is required for LC-HPC and is outlined in the concrete special provision. In the first special provision, the temperature of the concrete was required to be between 10° and 24° C (50° and 75° F). The second version, 90M-7275 (LC-HPC-3 through 7) tightened the temperature range to 13° and 21° C (55° and 70° F), but allowed an additional 3° C (5° F) below or above this range if approved by the Engineer. This change was instituted to give the Engineer control of the design temperature, encouraging the concrete supplier to aim lower than the upper bound of 75ºF.

Concrete Testing

The frequency of concrete testing (slump, temperature, air content, and strength cylinders) is specified. For each placement, slump must be tested for each of the first three truckloads and then once for every two truckloads. Temperature is tested for every truckload. The air content is tested for each of the first three truckloads and then once for every four truckloads. For the first four versions of the special provisions, through LC-HPC-11, one set of at least five strength cylinders is required for each deck or major mix design change, with three of the cylinders cured under standard laboratory conditions and two cylinders cured in the field. The fifth version, 90P-5095, beginning with LC-HPC-12, and all subsequent versions require at least two sets of five cylinders per deck or major mix design change, sampled from at least two different truckloads evenly spaced throughout the placement. The specifications indicate that the Engineer will reject concrete that does not comply with the specifications.

The third version of the special provision, 90M-7295 (LC-HPC-8, 9 and 10) and all subsequent versions, clarifies the location of concrete testing, that is, the concrete must meet specifications at the point of deposit on the bridge deck.

In an effort to more accurately reflect the testing rate capacity of inspectors and concrete testers for each bridge deck in Kansas, the Phase 2 specifications reduce the frequency of testing. The new specifications require that for each placement, slump must be tested for each of the first three truckloads and then once for every three truckloads. Temperature is tested for every truckload, measured at the truck discharge and from each sample made for slump determination. The air content and unit weight are tested for each of the first three truckloads and then once for every six truckloads.

Mixing, Delivery, and Placement Requirements for LC-HPC

Criteria for mixing, delivery, and placement of LC-HPC covered in the special provisions include mixing time, ambient air temperature, cold weather provision, and hot weather provisions.

As noted previously, slump control in the field may be accomplished by redosing with up to 50% of the original dose of the plasticizing admixture. The Engineer may alternatively allow up to 10 L/m^3 (2 $gallons/yd^3$) of water to be withheld from the mixture at the batch site, and if needed, added back into the truck at the construction site to adjust the slump to comply with the specifications. For the last three decks placed, however, withholding water was not allowed. For bridge LC-HPC-12 in Lyon County, slump was controlled by adjusting the quantity of mid-range water reducer with no water withheld from the mixture. Withholding water was not allowed for bridges LC-HPC-13 and 9 in Linn County. On bridge LC-HPC-13, initially the ready-mix supplier met the specifications for the qualification slab by holding 10 L/m^3 (2 gal/yd^3) of water and adding a mid-range water reducer, but was required to add all of the water at the batch plant for the bridge deck placement – a water reducer was, therefore, not required. For LC-HPC-9, the concrete supplier withheld water from the first four trucks delivered to the deck, but it was added back before testing and placement. The Phase 2 specifications required all water to be added at the plant, prohibit the addition of any water after initial batching, and allow slump to be adjusted only by the addition of an approved water reducing admixture.

The specifications require the concrete batch plant to have sufficient batching and delivery capacity to ensure that the concrete is supplied at a rate sufficient to provide for proper handling, placing, and finishing. The specifications also require that the Engineer inspect and approve the concrete batch plant and that plant/batch site approval may be rescinded at any time for failure to comply with the specifications.

The concrete special provisions include placement limitations for both cold weather and hot weather construction. For any weather, the concrete temperature at placement is required to be between 10º and 24ºC (50º and 75ºF). Cooling of the concrete may be required during hot weather using methods such as chilled water, ice as a partial replacement for mix water, shading or cooling the aggregates, or liquid nitrogen injection. Concreting operations in cold weather must be discontinued if the ambient air temperature drops below 4ºC (40ºF) and cannot resume until rising air temperatures reach 2ºC (35ºF). Concrete may not be placed if air temperatures are expected to drop more than 14ºC (25ºF) below the temperature of the concrete during the first 24 hours after placement unless insulation is provided for both the deck and the girders. Concrete may not be placed if the ambient air temperature is less than –7ºC (20ºF). Separate cold weather curing requirements are included in the construction special provisions, which are discussed later. The Phase 2 recommended concrete specifications have additional air temperature requirements. Concreting operations in cold weather must be discontinued if the ambient air temperature drops below 4ºC (40ºF) and cannot resume until rising air temperatures reaches 4ºC (40ºF). If the forecasted maximum air temperature for the 24-hour period after casting is expected to be between 13º and 16ºC (55º and 60ºF), then the air temperature must reach 7ºC (45ºF) before concreting operations may begin. Similarly, if the forecasted maximum air temperature is expected to exceed 16ºC (60ºF), then the air temperature must reach 10º C (50º F) before concreting operations may begin. LC-HPC-9, 12 (phases 1 and 2) and 13 were constructed using this requirement, as described in Chapter 5.

The first versions of the LC-HPC special provisions contain limitations on the concrete time-to-placement, which are nearly the same as the standard KDOT specifications. The maximum time limit for concrete to be placed after the addition of water to cement is either one or one-and-a-half hours, depending on the ambient air temperature as outline in Table 4.2. These requirements were removed from the fifth version of the special provision, 90P-5095 (LC-HPC-12), and all subsequent versions because it proved to be an unnecessary burden to the contractor on bridge LC-HPC-7. For LC-HPC-7, a longer haul time necessitated placement times greater than 1 hour after batching. The placement of LC-HPC-12 also necessitated placement times of up to 1.5 hours. The low concrete temperature allows the concrete to remain plastic and maintain its workability for increased placement times even with air temperatures above 24ºC (75ºF).

Qualification Batch

A field qualification batch, called a "trial batch" in the first and second versions of the special provisions is required. A qualification batch consists of one truckload or a minimum of 5 cubic meters (6 cubic yards) of concrete that meets all project specifications and is produced at least 35 days prior to placement of the qualification slab and the bridge deck. The qualification batch must be produced with the same materials and from the same plant as will be used for the qualification slab and the bridge deck. The haul time is simulated for the qualification batch. Documentation must be submitted stating that the qualification batch concrete has met the requirements for air content, slump, concrete temperature, compressive strength, and unit weight when evaluated after the simulated haul time. On a number of occasions, the qualification batch had to be repeated until it was demonstrated that the mix met all of the specification requirements.

The third version of the special provision, 90M-7295, starting with LC-HPC-8, and all subsequent versions, changed the terminology from "trial batch" and "trial slab" to "qualification batch" and "qualification slab" (discussed in Section 4.3.4). The purpose of the change was to emphasize that these items must meet the specifications and are subject to approval.

The fifth version of the special provision, 90M-5095 (LC-HPC-12) introduced requirements for documentation to be submitted for the qualified batch of concrete.

4.3.3 Aggregates

The aggregate special provision for LC-HPC, "Special Provision to the KDOT Special Provision to the 1990 Standard Specifications - Low Cracking High

Performance – Aggregates for Concrete," has undergone five minor revisions since the first version (90M-7182), for a total of six versions. The special provision designations for the six versions are provided in Table 4.3, and copies of the Special Provisions are found in Appendix C. Many of the requirements of the aggregate special provision are the same as the standard KDOT aggregate specifications (described in Section 4.2.3). The key differences are focused on the absorption limit for the coarse aggregates and the requirements for an optimized (combined) gradation. The requirements for the materials and optimized aggregate gradations are outlined next.

Material Requirements

The aggregate special provision contains requirements for aggregate absorption limits and limits on deleterious substances. The durability-focused requirements for soundness, degradation, deleterious substances, and alkali-silica reactivity are the same as appear in the standard KDOT specifications (described in Section 4.2.3).

LC-HPC decks contain granite or other highly durable coarse aggregate with low absorption. The low absorption reduces slump loss over time and helps maintain workability if the concrete is pumped. The aggregate special provisions require the maximum allowable absorption for coarse aggregate to be 0.7% for LC-HPC, in contrast to the standard KDOT aggregate specifications, which allow up to 2.0% absorption for the coarse aggregate. The Kansas City Metro Materials Board allows a maximum absorption of 0.5%. The LC-HPC special provisions for coarse aggregate allow a maximum of 2.5% to pass the 75 μm (No. 200) sieve, the same as the standard KDOT specifications, whereas the Kansas City Metro Materials Board allows only 0.5%. The predominant naturally occurring coarse aggregate in Kansas is limestone, which generally has higher absorption values. For reference, the KDOT Class 1 approved limestone used on pavements in Kansas generally has a bulk specific gravity (saturated surface-dry condition) of 2.56 to 2.58 and typical absorption values of 2.5% to 3.0%. Thirteen of the bridge decks contain granite imported from Arkansas and one deck contains granite imported from Oklahoma. The sixth version of the aggregate special provisions, LCHPC-2, as provided by the City of Overland Park, Kansas, specifically requires a granite coarse aggregate, with a maximum absorption of 0.5% and a maximum of 0.5% passing the 75 μm (No. 200) sieve for Bridge LC-HPC-14. The Phase 2 recommended specifications continue to require a maximum absorption of 0.7% for the coarse aggregate and up to 2.5% passing the 75 μm (No. 200) sieve.

Naturally occurring or manufactured sand is allowed as fine aggregate, with a maximum of 2.0% of the material passing the 75 μm (No. 200), as required in both the standard KDOT specifications and the Kansas City Metro Materials Board requirements. The angular nature of manufactured sand is not addressed in the aggregate specification, although a warning is added in the Phase 2 aggregate specifications indicating that manufactured sands used to obtain optimum gradations have caused difficulties in pumping, placing, and finishing. It is the responsibility of the contractor and concrete supplier to ensure that the mix meets all specifications and is workable and placeable. This includes any workability issues resulting from the use of manufactured sand. The qualification batch and the qualification slab, discussed later, are measures added to the specifications that the contractor and concrete supplier can and should use to demonstrate that the materials are adequate for the construction of the LC-HPC deck. They have not always been used appropriately. As will be described in the Chapter 5 experiences, adjustments were required on several decks to obtain workable, placeable concrete. All of the LC-HPC decks contained natural river sand, but five of the LC-HPC decks also contained manufactured sand (crushed granite) to help increase the percent retained on the intermediate sieves. The sixth version of the special provisions (LCHPC-2), as provided by the City of Overland Park, Kansas, specifies a maximum of 45% natural sand for Bridge LC-HPC-14. Additional details about the aggregates used in the decks are described in detail by Lindquist et al (2008).

Optimized Aggregate Gradation Requirements

The aggregate special provisions require that the combined (total) aggregate gradation ("total mixed aggregate," or TMA) be *optimized* and provides gradation limits for the combined gradation.

Aggregate gradation optimization involves choosing aggregate proportions for a particular set of aggregates so that the combined aggregate gradation contains all size fractions, including intermediate-sized particles, to provide a dense aggregate gradation. This allows the paste content (demand) of the mixture can be minimized, while at the same time providing enhanced workability and cohesion to the mixture. Aggregate optimization is further discussed in Section 2.6. In this study, a method of optimizing the aggregate gradation was developed, called the KU Mix© method. A Microsoft Excel spreadsheet enhanced with Visual Basic for Applications was designed to perform the KU Mix© optimization method. The spreadsheet is available for free download at www.iri.ku.edu. Other approved methods, such as the Shilstone (1990) method, may also be used to optimized the aggregate gradation.

The LC-HPC aggregate special provisions detail gradation limits for the combined, optimized aggregate gradation. The limits are written to require a true nominal 25.0-mm (1-in.) maximum size aggregate (MSA), with 2–6% retained on the 25.0-mm (1-in.) sieve, and a maximum of 2.5% material passing the 75-µm (No. 200) sieve. This represents an increase in the MSA from the standard KDOT specification requirements of 19 mm (¾ in.). Often the standard KDOT mixtures contain an actual (provided) MSA of just 13 mm (½ in.). Requiring 2 to 6% retained on the 25.0-mm (1-in.) sieve, in conjunction with aggregate optimization, allows for the LC-HPC mixtures to contain more aggregate and less paste, thus reducing shrinkage and cracking. The combined aggregate gradation requirements for the deck and rails in the six versions of the special provision are shown in Table 4.4.

The combined gradation limits for the LC-HPC decks were tightened slightly for the middle sieve sizes, 19.0-mm (3/4-in.) to 1.18-mm (No. 16) between the first, 90M-7182 (LC-HPC1 through LC-HPC-7) and the second, 90M-7326 (LC-HPC-8, 9, and 10) special provisions. The modified limits more accurately reflect the optimized aggregate gradations and include additional gradation requirements for the bridge rail. It is important to note that gradation limits neither take the place of nor guarantee an optimized gradation. An optimized aggregate gradation is determined using an approved method, such as the KU Mix© method described above.

The barriers for LC-HPC-8, 9, and 10 were corral rails, which had small spacing between the reinforcing steel bars at the connection of the rail to the deck and only 25 mm (1.0 in.) cover. To improve consolidation in these areas with dense reinforcing and small clear spacings, and to reduce the risk of air pockets, the gradation for the rail was changed in the addendum, Addendum K7891, to the second version of the specification, 90M-7326, to eliminate the aggregate retained on the 25.0-mm (1-in.) sieve. The resulting new maximum sized aggregate (MSA) for the barrier was 19.0 mm (0.75 in.), and the other gradation limits for the barrier were not modified (reoptimized) for the smaller MSA and remained the same as for the deck.

The third special provision, 90M-7339 (LC-HPC-11), made the distinction between solid barrier rails (jersey barrier) and corral rails and includes separate gradation requirements for each case. The barrier rail gradation was the same as for the bridge decks, but the gradations for the corral rails contain a MSA of 19.0 mm (3/4 in.) and the limits reflect a re-optimized gradation for the smaller MSA.

The gradation limits for the corral rail were adjusted in the fourth version of the special provision, 90P-5085 (LC-HPC-12), while the deck and barrier gradation limits remain the same. No changes were made to the gradation limits in the fifth version, 90M-7359 (LC-HPC-13).

The sixth version of the special provision, LCHPC-2 (Bridge LC-HPC-14) does not include limit requirements for the material passing the 75-μm (No. 200) sieve for the blended aggregate.

Table 4.4 Combined aggregate gradation requirements for LC-HPC bridges

Sieve	Percent Retained on each Sieve†					
	Special Provision Version No. Special Provision Designation					
	1	**2-6**	**2**	**3-6**	**3**	**4-6**
	90M-7182	90M-7326 90M-7339 90P-5085 90M-7359 LCHPC-2	Addendum K7891	90M-7339 90P-5085 90M-7359 LCHPC-2	90M-7339	90P-5085 90M-7359 LCHPC-2
	Deck	**Deck**	**Rail‡**	**Barrier Rail**	**Corral Rail**	**Corral Rail**
37.5-mm (1½-in.)	0	0	0	0	0	0
25.0-mm (1-in.)	2–6	2–6	0	2–6	0	0
19.0-mm (¾-in.)	5–22	5–18	5–18	5–18	2–6	2–6
12.5-mm (½-in.)	8–22	8–18	8–18	8–18	8–20	8–20
9.5-mm (⅜-in.)	8–22	8–18	8–18	8–18	5–15	8–20
4.75-mm (No. 4)	8–22	8–18	8–18	8–18	5–15	8–20
2.36-mm (No. 8)	8–22	8–18	8–18	8–18	5–15	8–20
1.18-mm (No. 16)	8–22	8–18	8–18	8–18	5–15	8–20
600-µm (No. 30)	8–15	8–15	8–15	8–15	8–15	8–15
300-µm (No. 50)	5–15	5–15	5–15	5–15	5–15	5–15
150-µm (No. 100)	0–5	0–5	0–5	0–5	0–5	0–5

† Maximum of 2.5% passing the 75-µm (No. 200) sieve

‡ No distinction between barrier types. Gradation was not re-optimized.

4.3.4 Construction

Eight versions of the "Low Cracking High Performance – Construction" special provision to the KDOT 1990 standard specification were written. Special provision 90M-7190 was the first construction specification for LC-HPC bridge decks, and covered the first two LC-HPC bridge decks (LC-HPC-1 and 2), which were let in a single contract. Special provision 90M-7276, the second construction specification, covers five LC-HPC bridge decks (LC-HPC-3 through 7), let in two contracts. Special provision 90M-7296 is the third version of the construction specification, covering three LC-HPC decks (LC-HPC-8, 9 and 10) in one contract. This special provision was closely followed by an addendum to the special provision, K7891 Addendums, here considered the fourth version of the specification, covering the same three bridge decks. Special provision 90M-7332 is the fifth version, covering LC-HPC-11. Special provision 90P-5097 is the sixth version of the construction specification, covering LC-HPC-12. Special provision 90M-7361 is the seventh version of the construction specification, covering LC-HPC-13. Special provision LCHPC-3 “Low Cracking - High Performance Concrete (LC-HPC) Construction” is the eighth version of the construction specification, covering LC-HPC-14 located in Overland Park, Kansas, and reflects changes required by the city engineer. Copies of these Special Provisions are found in Appendix C. Specification versions are correlated with the bridges numbers later in Table 4.5 (Section 4.4).

The construction of LC-HPC decks includes requirements for contractor preparation, quality control, concrete temperature control, control of the evaporation rate, placement, consolidation, finishing, fogging, curing (including inspection), drying after the curing period, grinding, grooving, the construction of the qualification slab, and a post-construction conference.

Contractor Preparation for LC-HPC Construction

The successful implementation of the LC-HPC construction procedures is critical to preventing cracking.

To assist in contractor preparation for LC-HPC construction, a number of methods for educating the contractors during the bidding and contractor-selection process were considered. Ideally, requirements would be established to prequalify contractors to bid on LC-HPC projects. These might include attending training on LC-HPC construction, passing an exam, or demonstrating skills prior to selection. Realistically, KDOT determined that they could not prequalify contractors, but that an effort to educate the contractors prior to bidding should be used. For all contracts incorporating LC-HPC construction, the prime contractor was required to attend a pre-bid conference (Special Provision 90M-0036). During the pre-bid conference, special attention was drawn to the bridges with LC-HPC bridge decks. Background information about cracking and the causes of cracking in bridge decks was presented. The unique characteristics and requirements in the new LC-HPC Special Provisions for the concrete, aggregate, and construction were described. This information was intended to help inform and aid the bidding process. However, because the bridge sub-contractor, concrete supplier, and other subcontractors were not required to attend the pre-bid conference, they were not necessarily informed about the special requirements for an LC-HPC deck.

The mandatory pre-bid conference was, however, a helpful first step toward preparing contractors and ensuring successful completion of the many special requirements for LC-HPC construction. The qualification slab, discussed later, became the second preparation step for personnel in the field. During construction of the qualification slab, KU personnel worked together with KDOT inspectors, engineers, and the bridge contractor to demonstrate successful completion of all LC-HPC requirements. The qualification slab has been an invaluable tool for contractors to become familiar with the specialized process and to address concerns prior to the placement of the bridge deck.

Quality Control Plan

Limiting the evaporation rate during concrete placement plays an important role in the prevention of cracks in bridge decks because of the role of evaporation in the formation of plastic shrinkage cracks. The special provisions for LC-HPC construction require the contractor to submit a Quality Control Plan detailing the equipment and procedures for determining and controlling the evaporation rate. As specified, the Quality Control Plan is to be submitted during the preconstruction meeting.

Concrete Temperature Control

As discussed previously in Section 4.2.3, the plastic concrete must be between 13ºC (55ºF) to 21ºC (70ºF) at the time of placement. With the approval of the

Engineer, this range may be extended by 3ºC (5ºF), above or below, to 10ºC (50ºF) to 24ºC (75ºF). Limiting the maximum concrete temperature provides several benefits to reduce the risk of cracking, including reducing thermal stresses due to heat of hydration, lowering the evaporation rate, which reduces the potential for plastic shrinkage cracking, and importantly, increase the period during which the concrete workability is maintained.

Control of Evaporation Rate

The construction special provisions require that the evaporation rate to be less than 1.0 kg/m^2/hr (0.2 lb/ft^2/hr). Higher evaporation rates increase the probability of plastic shrinkage cracking. The evaporation rate is a function of air temperature, concrete temperature, wind speed, and relative humidity. Measurements of each must be taken and recorded, and the evaporation rate must be calculated just prior to and at least once per hour during placement of LC-HPC concrete. The special provisions stipulate that if the evaporation rate equals or exceeds 1.0 kg/m^2/hr (0.2 lb/ft^2/hr), then measures must be taken to reduce the evaporation rate below 1.0 kg/m^2/hr (0.2 lb/ft^2/hr) before concrete placement may begin. The special provisions do not allow fogging to be considered in the determination of the evaporation rate.

Placement

The special provisions require LC-HPC to be placed by conveyor belt or concrete bucket. Pumping is also allowed for LC-HPC if the contractor can demonstrate that the approved mix can be pumped, either during the construction of the qualification slab or at another time (with prior approval of the Engineer) at least 15 days prior to placing concrete in the deck. In general practice, pumping concrete requires an increase in the paste (water and cement) content to lubricate the pump. This practice is not allowed for LC-HPC construction because increases in paste lead to increases in cracking. The method of placement can affect the plastic properties of the concrete, such as the slump and air content. The concrete must meet specifications at the point of deposit on the deck, regardless of the method of placement.

Consolidation

Consolidation using vertically mounted internal gang vibrators is required for LC-HPC construction. The LC-HPC construction special provisions, however, have not addressed consolidation because the subject is covered by the standard KDOT specifications. The new Phase 2 LC-HPC specifications do cover consolidation, closely mirroring KDOT standard specifications for consolidation on bridge decks. A description of the consolidation requirements is provided previously in Section 4.2.4. The Phase 2 recommended specifications require the same gang vibration equipment as the 2007 KDOT Standard Specifications, but additional descriptive requirements reflecting good concreting practices for consolidation with vibrators are also included. Vibrators should be extracted from the concrete at a rate to avoid leaving voids or holes in the concrete and may not be dragged horizontally through LC-HPC. Any voids in the concrete left by workers, either walking in the consolidated concrete or otherwise, should be reconsolidated. The KDOT standard specifications and all versions of the LC-HPC specifications have required positive control of the vibrators using a timed light, buzzer, automatic control or other approved method; this has not been satisfied for any LC-HPC placement to date.

Finishing

Concrete strike-off is accomplished using a vibrating screed or a single-drum roller screed. Double-drum screeds have generally not been permitted because they have the potential to work more paste to the top surface of the concrete deck than single-drum screeds. A thicker layer of paste at the surface of the deck will increase the potential for plastic shrinkage and drying shrinkage cracking. The second and third placements of LC-HPC-14, however, were finished with a double-drum roller screed with no problems apparent during construction.

The special provisions allow the surface to be finished after strike-off with a burlap drag or metal pan mounted on the finishing equipment. The addition of water, finishing aids, or precure material to assist in the finishing operations is prohibited. Working water into the surface increases the *w/cm* ratio at the surface, increasing the risk of cracking. The surface finish should be reasonably true and even, free from stone pockets, excessive depressions or projections beyond the surface. Tining of the plastic concrete surface is also prohibited because tining delays the initiation of curing. Grinding and grooving of the hardened concrete is required, as described later.

Fogging

The construction special provisions require continuous fogging of the entire placement width immediately behind finishing operations for all LC-HPC bridge deck placements. Fogging equipment is specified to be mounted on the finishing equipment or on equipment immediately following the finishing equipment. The purpose of fogging is to provide an area of high relative humidity above the surface of the concrete so as to lower the local evaporation rate at the surface and reduce the chances for plastic shrinkage cracking. The special provisions allow hand-held fogging apparatus only for those areas of the deck not covered by machine fogging or in the event that advancement of finishing is delayed. The effectiveness of hand-held fogging is considered to be highly dependent on the operator. The fog spray produced is specified so as to not deposit excess water on the surface of the concrete. A "gloss to semi-gloss water sheen" should be maintained on the surface until the curing is applied.

In practice, fogging was rarely needed due to low evaporation rates and the consistent misuse of fogging as a finishing aid was a considerable problem. For most placements, fogging was stopped due to equipment leakage or misuse by workers as a finishing aid. In most cases, the machine-mounted fogging equipment initially dripped water onto the surface of the concrete or it was mounted with the misting nozzles pointed down, spraying water directly onto the surface of the concrete. The water was then worked into the surface of the deck during the final finishing operations. In these cases, the fogging equipment was turned off and using the water as a finishing aid was not allowed. Only one machine-mounted fogging system, for LC-HPC-11, did not drip water and was used properly.

Curing

Curing must begin immediately after finishing and continue uninterrupted for at least 14 days. The Water with Waterproof Cover method, described next, was specified for curing all LC-HPC decks. Pedestrian walkways are specified to be cured in the same manner as the bridge deck. Versions 3 through 7 of the construction Special Provisions required the barriers to be cured in the same manner as the decks, except that fogging was not required for the barriers. The special provisions prohibit the use of curing compounds during the 14-day curing period.

Water with Waterproof Cover Method. As described previously, fogging is to begin immediately behind the finishing operations to maintain a "gloss to semi-gloss sheen" on the surface of the concrete until burlap is applied. Water from the fogging operations is not allowed to drip, flow or puddle on the concrete surface. One layer of saturated burlap must be placed on the surface of the plastic concrete within 10 minutes after concrete strike-off, followed by a second layer of saturated burlap within 5 minutes. The surface of the concrete must not be allowed to dry at any time after strike-off until the end of the 14-day curing period. The burlap must be maintained in the fully wet condition using a misting hose, self-propelled machine-mounted fogging equipment with effective area spanning the deck width, or other approved methods, until the concrete has set sufficiently to allow foot traffic. Soaker hoses are then placed on the burlap and continuously supplied with running water so the entire concrete surface is kept wet. Within 12 hours, white polyethylene film must be placed and secured over the entire concrete surface to form a complete waterproof cover. Curing must be checked every 6 hours for the entire 14-day curing period to ensure that the entire concrete surface is continuously wet. Documentation of the inspections must be provided to the Engineer, including any deficiencies and corrective measures taken. If the curing material is removed for any reason, the exposed area must be kept continuously wet. The specified curing conditions must be reinstated as soon as possible, and the situation documented.

The intent of the Water with Waterproof Cover method is simply to never allow the concrete to dry out until the curing period is complete. Prevention of drying is of primary importance. Immediate covering of plastic concrete with presoaked (saturated) burlap reduces the time of surface exposure to drying. The burlap must be completely saturated before placement begins. Burlap that is not saturated will act as a wick, drawing moisture out of the plastic concrete. The provisions requiring the placement of soaker hoses and also requiring keeping the burlap wet by hand-held spray until the soaker hoses are in place help to ensure that the burlap will remain wet, protecting the concrete from drying. The polyethylene film waterproof cover reduces evaporation of water. The continuous water supply also acts as a heat exchanger, cooling the concrete during the hydration process. Frequent inspection during the entire 14-day curing period is necessary around the clock to ensure corrective measures are taken immediately if the burlap begins to dry out. This requirement is intended to protect against any drying conditions that could arise in a construction environment, for example, wind blowing the waterproof cover off the deck or the water source being interrupted for an extended period of time, allowing concrete to dry.

Cold Weather Curing. When concrete is being placed and the ambient air temperatures are expected to fall below 5ºC (40ºF) during the curing period or more than 14ºC (25ºF) below the temperature of the plastic concrete during the first 24 hours after placement, precautions are required to protect the deck and the girders, including straw, additional burlap, or other suitable blanketing materials, and/or housing and artificial heat to maintain the concrete and girder temperatures between 13ºC (55ºF) and 24ºC (75ºF). The area around the girders must be enclosed and heated so that the air temperature surrounding the girders is as close as possible to the concrete and between 13ºC (55ºF) and 24ºC (75ºF). Cold weather protection and curing materials must be removed in such a way that the concrete temperature does not fall more than 14ºC (25ºF) in 24 hours.

Drying after the Curing Period

After the curing period is over, reducing the rate of drying will allow the concrete extra time to creep and reduce stresses due to drying shrinkage, which can cause cracking at early ages. Therefore, the specifications state that after the 14-day curing period, the rate of drying is to be reduced by the application of a curing membrane. The curing membrane serves to slow the rate of drying, not to provide additional curing. Within 30 minutes after the curing materials (wet burlap and polyethylene film) are removed, two coats of curing membrane must be applied to the surface of the concrete while it is still wet. The second coat should be sprayed immediately after the first coat and at right angles to the first application. The goal is to provide a complete and uniform coating. The curing membrane may not be disturbed or marred for at least 7 days. Any area with marred or disturbed membrane must receive an additional coating.

Grinding and Grooving

After the curing period (14 days) and the drying period (7 days) with curing membrane is completed, grinding and grooving of the hardened concrete surface are required for LC-HPC decks. The first two versions of the construction special provisions, 90M-7190 (LC-HPC-1 and 2) and 90M-7276 (LC-HPC-3 through 7), required grinding of the finished surface to achieve a plane surface, correcting surface variations exceeding 3 mm (1/8 in.) in 3 m (10 ft). Based on the first LC-HPC bridge deck placement and at the suggestion of the KDOT construction engineer, the third version of the construction special provision, 90M-7296, beginning with LC-HPC-8, and all subsequent versions require grinding of the entire deck surface. Subsequent

LC-HPC experience, however, indicated that this was not needed as most decks did not require any grinding. The final texture of the deck is achieved by placing transverse grooves in the hardened concrete surface to improve vehicle traction. The grooves are approximately 5 mm (3/16 in.) wide, 3 mm (1/8 in.) deep, and 20 mm (3/4 in.) on center. Tining of plastic concrete is not allowed for LC-HPC construction.

Qualification Slab

After the qualification batch of LC-HPC concrete has been approved, the construction of a qualification slab, originally called a "trial slab" in the first and second versions of the construction special provisions (LC-HPC-1 through 7), is required for each LC-HPC bridge deck. The purpose of the qualification slab is for the contractor to demonstrate the ability to place, finish, and cure the LC-HPC bridge deck according to the specifications. The qualification slab helps ensure that there are no "surprises" during the construction of the bridge deck. As a result, the contractor's first experience with LC-HPC construction is on a qualification slab, not on the deck, where the performance is most critical. The crews gain hands-on experience and learn the new techniques. This helps get the "kinks" out of the process for the contractor, concrete supplier, inspectors, and owner before the day that the deck is placed.

The qualification slab is constructed 15 to 45 days prior to placing concrete in the bridge deck (at least 30 days prior in the first and second versions of the special provision). The qualification slab is identical to the deck in geometry, except it is not required to be elevated. The dimensions of the qualification slab are shown in the contract documents, typically 10 m (33 ft) long with the same width as the actual bridge deck, containing the same reinforcement. The methods, equipment, crews and concrete are required to be the same as for the placement of the bridge deck. For approval purposes, the specifications require four full-depth 100-mm (4-in.) diameter cores to be cut from qualification slab, one from each quadrant, within a day of placement and submitted to the Engineer for visual inspection of the degree of consolidation. Acceptance of the qualification slab and permission to place the deck are contingent upon the contractor's ability to adequately place, consolidate, finish, cure the concrete. If necessary, the qualification slab would be repeated at the owners expense. None of the qualification slabs were repeated, and the qualification slab requirement was waived for some LC-HPC decks for which the contractor had significant, successful, and recent LC-HPC placement experience.

Post-Construction Conference

After completion of construction of an LC-HPC bridge deck, a post-construction conference is held to discuss the problems and successes for the project. All parties that participated in the planning and construction of the deck attend the conference.

4.4 BRIDGES

Fourteen LC-HPC bridge decks, 11 corresponding control decks, and one alternate control deck have been constructed in Kansas, for a total of 26 bridges. The construction of all of the LC-HPC and control decks has been completed.

The LC-HPC bridge decks and the corresponding control decks were chosen to have consistent design parameters to maintain fair and consistent comparisons between bridges. Except for two LC-HPC bridges and one control bridge with prestressed concrete girders, the bridges have steel girders. Four LC-HPC decks have non-integral end conditions, and one LC-HPC deck has one integral and one non-integral end condition. Five control bridges have non-integral end conditions and one control bridge has one integral and one non-integral end condition. Most of the bridges have no skew or only minor skew. Four of the LC-HPC bridges have skews ranging from 18 to 35 degrees, and three of the control bridges have skews ranging from 21.5 to 24 degrees. Two LC-HPC and two control bridges have curved roadways.

The decks are either LC-HPC construction or, for the control decks, the standard KDOT systems, either monolithic (full-depth) or a silica fume overlay (SFO) deck.

The bridges are located in the counties of Wyandotte, Jackson, Johnson, Reno, Linn, and Lyon, with most in the northeast quadrant of the state, as shown in Fig. 4.2. The 26 bridges in this study were let under 11 separate contracts. Some bridges were let in groups in a large project, while others were the only bridge let in the contract. Seven different contractors were responsible for the construction of bridge decks in this study.

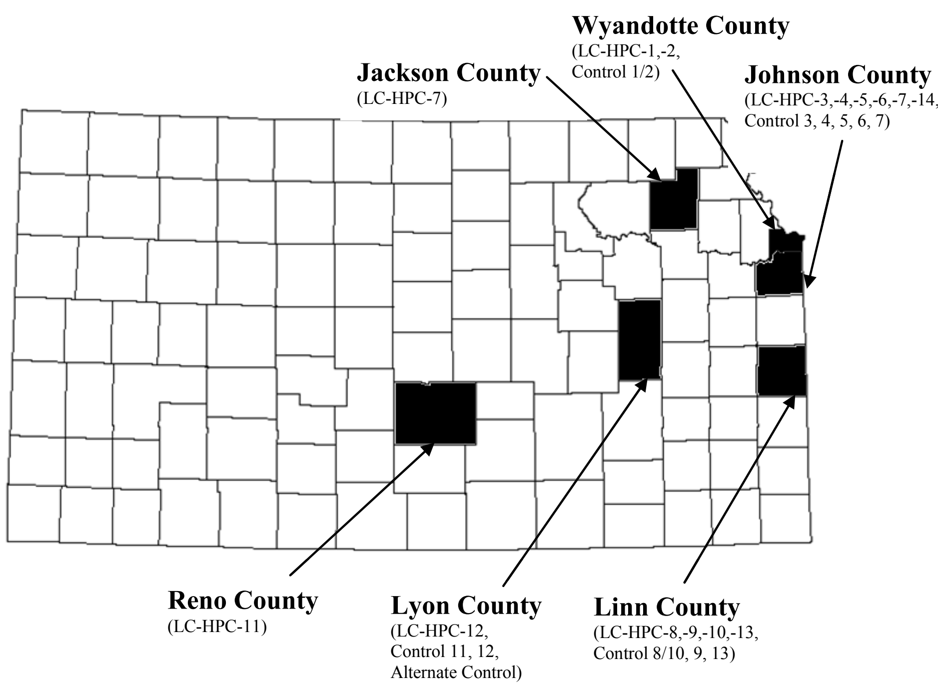


Fig. 4.2. Kansas counties with LC-HPC or control bridges

The individual bridge numbers were assigned in the order they were let. The bridge numbers, arranged by contract group, let date, construction date, and contractor are listed in Table 4.5a. The county, girder type, and protection system are listed in Table 4.5b. KDOT bridge numbers, location descriptions, project numbers, and contract numbers are provided in Appendix D. County locations within the State of Kansas are shown in Fig. (4.2). Additional details for each bridge are found in Appendix D.

Table 4.5a LC-HPC and control bridges in Kansas – Let Date, Construction Date and Contractor

Contract Group	Bridge No.	Let Date	Date of Construction Completion	Contractor (prime/sub)
1	LC-HPC-1	9/15/2004	11/2/2005	Ellis/Clarkson
	LC-HPC-2		9/13/2006	Ellis/Clarkson
	Control 1/2		10/28/2005	Ellis/Clarkson
2	Control 11	1/19/2005	3/28/2006	Cohron
3	LC-HPC-3	8/17/2005	11/13/2007	Clarkson
	LC-HPC-4		10/2/2007	Clarkson
	LC-HPC-5		11/14/2007	Clarkson
	LC-HPC-6		11/3/2007	Clarkson
	Control 3		7/17/2008	Clarkson
	Control 4		11/16/2007	Clarkson
	Control 5		11/25/2008	Clarkson
	Control 6		10/20/2008	Clarkson
4	Control 7	8/17/2005	9/15/2006	Clarkson
5	LC-HPC-7	10/19/2005	6/24/2006	Koss/Capital
6	LC-HPC-8	7/19/2006	10/3/2007	Koss/Cohron
	LC-HPC-9		4/15/2009	Koss/United
	LC-HPC-10		5/17/2007	Koss/Cohron
	Control 8/10		4/16/2007	Koss/Cohron
	Control 9		5/28/2008	Koss/United
7	LC-HPC-11	8/16/2006	6/9/2007	Koss/King
8	LC-HPC-12	11/15/2006	Phase 1 4/4/2008; Phase 2 3/18/2009	Cohron
	Control 12		4/14/2009	Cohron
9	LC-HPC-13	1/17/2007	4/29/2008	Koss/Beachner
	Control 13		7/25/2008	Koss/Beachner
10	LC-HPC-14	3/26/2007	5/31/08	Pyramid
NA	Control Alt[4]	3/16/2005	4/16/2007	King

[4] Control Alt is a monolithic deck included as an additional control deck.

Table 4.5b LC-HPC and control bridges in Kansas – County, Girder Type, Deck Type

Bridge No.	Kansas County[1]	Girder Type	Deck Type[2]
LC-HPC-1	WY	Steel	LC-HPC
LC-HPC-2	WY	Steel	LC-HPC
Control 1/2	WY	Steel	SFO
Control 11	LY	Steel	SFO
LC-HPC-3	JO	Steel	LC-HPC
LC-HPC-4	JO	Steel	LC-HPC
LC-HPC-5	JO	Steel	LC-HPC
LC-HPC-6	JO	Steel	LC-HPC
Control 3	JO	Steel	SFO
Control 4	JO	Steel	SFO
Control 5	JO	Steel	SFO
Control 6	JO	Steel	SFO
Control 7	JO	Steel	SFO
LC-HPC-7	JA	Steel	LC-HPC
LC-HPC-8	LN	PS[3]	LC-HPC
LC-HPC-9	LN	Steel	LC-HPC
LC-HPC-10	LN	PS[3]	LC-HPC
Control 8/10	LN	PS[3]	monolithic
Control 9	LN	Steel	SFO
LC-HPC-11	RN	Steel	LC-HPC
LC-HPC-12	LY	Steel	LC-HPC
Control 12	LY	Steel	SFO
LC-HPC-13	LN	Steel	LC-HPC
Control 13	LN	Steel	SFO
LC-HPC-14	JO	Steel	LC-HPC
Control Alt[4]	LY	Steel	monolithic

[1] County abbreviations: WY = Wyandotte, JO = Johnson, JA = Jackson, LN = Linn, RN = Reno, LY = Lyon
[2] Deck Types: LC-HPC = Low-Cracking High-Performance deck; SFO = Silica Fume Overlay deck; monolithic = monolithic deck cast without a SFO.
[3] PS = Prestressed concrete
[4] Control Alt is a monolithic deck included as an additional control deck.

Chapter 5

LC-HPC AND CONTROL BRIDGE DECK CONSTRUCTION EXPERIENCES AND CRACKING RESULTS IN KANSAS

5.1 GENERAL

This chapter describes the construction experiences and lessons learned for the first 14 Low-Cracking High-Performance Concrete (LC-HPC) bridge decks in Kansas and the accompanying 12 control bridges. The chapter is divided into two sections covering (1) experiences with LC-HPC and control bridge deck construction, and (2) cracking results for the LC-HPC and control bridge decks. The experiences with LC-HPC bridge decks presented in this chapter are primarily focused on the construction methods and experiences. A brief overview of the materials and production is provided, and those related items that impact the construction are discussed. A complete discussion of the LC-HPC materials and production is presented in the companion report by Lindquist et al. (2008).

The LC-HPC bridge decks in Kansas are constructed in accordance with the standard KDOT specifications, supplemented by special provisions for aggregates, concrete, and construction, as described in Chapter 4. The control bridge decks are constructed in accordance with the standard KDOT specifications, also described in Chapter 4. An overview of each bridge deck included in this study is provided in Section 4.4; details related to the design are included in this chapter.

Definitions related to the parameters discussed in the experiences are outlined in Section 5.2. The construction experiences and lessons learned are presented in Section 5.3, and the results of the cracking surveys are presented in Section 5.4.

5.2 DEFINITIONS

This section defines the parameters used in Section 5.3, time to burlap placement, average haul time, and average placement rate, and describes how these parameters are calculated.

5.2.1 Measuring the Time to Burlap Placement

The construction specifications require that the concrete be covered with saturated burlap within 10 minutes after strike-off. Data was collected during each placement to determine whether this requirement was satisfied. The time to placement of burlap for multiple stations along the deck, including the station location, the time of concrete strike-off by the roller screed or by pans (if used) attached to the roller screed, and the time that the first layer of saturated burlap is placed on the concrete surface were recorded. The time to burlap placement for each station equals the time difference between strike-off and placement of the burlap.

5.2.2 Estimating the Average Haul Time

The average haul time is estimated from the trip tickets for each placement. The haul time for each truckload of concrete it calculated as the time difference between batching and the beginning of truck discharge. Haul time includes the time between truck arrival on site (and sampling if applicable) and discharge. For the purpose of accepting trucks for placement in a structure, the time from batching to discharge is the time of concern. Haul time from batching to arrival on site is not of interest for the purpose of this analysis.

5.2.2 Estimating the Average Placement Rate

The average placement rate is the volume of concrete placed in the deck, including end walls and diaphragms cast integrally with the deck, divided by the total time of placement. The time of placement is defined as the period between initial concrete placement and placement of the last piece of burlap to initiate curing.

For some bridges, the volume of concrete placed was obtained from the trip tickets, and for some decks (where the trip tickets were not available) it was estimated as the horizontal surface area of the deck times the deck thickness, not including the concrete in the end walls. Neither method accounts for the exact volume of concrete in the deck. These are estimates and are meant to provide a general picture of the speed of the construction for each bridge and each placement. The average placement rate is highly variable and is influenced by many factors, including placement method (pump, bucket, conveyor), material production and delivery rates, concrete testing, and burlap placement.

5.3 LC-HPC AND CONTROL BRIDGE DECK CONSTRUCTION EXPERIENCES IN KANSAS

The experiences gained and lessons learned during the construction of the LC-HPC bridge decks in Kansas are described in this section. The construction meetings and construction of the qualification slabs and LC-HPC bridge decks are covered, emphasizing experiences with the construction procedures and methods, as well as the personnel involved and lessons learned. Experiences related to the concrete mix design, aggregates, qualification batch, concrete testing, and field production are reviewed here, but are discussed in detail by Lindquist et al. (2008). Control bridge design, materials, and construction are described as available from KDOT records. The experiences are presented in order of construction, although bridges let in multiple-bridge contracts are presented together. Exceptions to the specifications are described and special considerations for each bridge are noted. Construction, design, and materials data for the bridges in this study are provided in Appendix D.

5.3.1 LC-HPC Bridge 1

The first two LC-HPC bridge decks let in Kansas (LC-HPC-1 and LC-HPC-2) were part of a single contract, along with one control structure for both decks, Control

1/2. LC-HPC-1 is the eastbound (south half) bridge on Parallel Parkway over I-635 in Kansas City, KS. Control 1/2 is the westbound (north half) bridge on the same route and is described later. The contract was awarded to W. A. Ellis Construction who subcontracted the bridges to Clarkson Construction.

LC-HPC-1 was the first LC-HPC bridge deck constructed. Dates related to the construction of LC-HPC-1 are shown in Table 5.1. Two attempts were made to complete the qualification slab. The construction of LC-HPC-1 was completed successfully, with improvements in the process as construction progressed.

Table 5.1 – Construction Dates for LC-HPC-1

Item Constructed	Date Completed
Qualification Batch (Trial Batch)	6/20/2005
Qualification Slab (Trial Slab) for LC-HPC-1 Attempt 1	7/12/2005
Qualification Slab (Trial Slab) for LC-HPC-1 Attempt 2	9/8/2005
LC-HPC-1 Placement 1	10/14/2005
LC-HPC-1 Placement 2	11/2/2005
Post-Construction Meeting	2/20/2006

Design. The Parallel Parkway bridge over I-635 is a unique design that serves to solve traffic congestion problems at an interstate exit ramp within significant space constraints. It is a steel girder bridge with integral abutments and a 5° skew. The bridge, as a whole, is very wide – nearly as wide at 43.65 m (143.2 ft) as it is long at 47.30 m (155.2 ft). The bridge is actually two independent bridges, LC-HPC-1 (the eastbound portion) and Control 1/2 (the westbound portion), which together constitute the entire Parallel Parkway and I-635 interchange.

LC-HPC-1 is 47.30 m (155.2 ft) long with two spans with lengths of 23.27 m (77.6 ft), and is 22.90 m (75.13 ft) wide. It was constructed in two placements, each 11.84 m (38.84 ft) wide. The adjacent (and connected) Control 1/2 bridge was also constructed in two placements.

The first placement for LC-HPC-1 was on the south side of the bridge. The second placement was directly to the north of the first placement, and adjacent to Control 1/2. A Jersey barrier is located on the south edge of the first placement. Much of the surface area for the first placement does not support traffic, but is generally open space containing traffic signals and curb barriers for traffic, with the portions near each end of placement 1 used for exit/entrance ramp traffic from I-635. Most of the eastbound traffic lanes on Parallel Parkway are part of the second placement of LC-HPC-1. The LC-HPC-1 deck is 220 mm (8.7 in.) thick with No. 16 (No. 5) transverse reinforcing bars at 150 mm (5.9 in.) centers.

Concrete. Fordyce Concrete provided the concrete for the LC-HPC-1 and 2 decks, with a haul distance of 13.0 km (8.1 mi) and an average haul time of 16 minutes for LC-HPC-1. The concrete for both LC-HPC-1 and 2 had a cement content of 320 kg/m^3 (539 lb/yd^3), a *w/c* ratio of 0.45, and an air content of 8.0%. The aggregates included three granite coarse aggregates (Bulk Specific Gravity of the aggregate in the Saturated Surface-Dry contition, BSG_{SSD} = 2.63) and one natural river sand fine aggregate (BSG_{SSD} = 2.61). The total aggregate gradation for the qualification batch and qualification slab was originally optimized, but the gradation for the deck placement was not re-optimized to account for the as-delivered aggregate gradations. The actual gradation (as placed in the deck) was, therefore, out of specification (low) by 2% retained on the 2.36-mm (No. 8) sieve. The small difference did not appear to affect the contractor's ability to handle, place, or finish the concrete.

Qualification Batch. The qualification batch was produced on June 20, 2005 without KU personnel on site. The batch met the specifications for air content (6.5%) and slump [63 mm (2.5 in.)] but not concrete temperature. The air temperature on the day of the qualification batch ranged from 16° to 31°C (61° to 87°F). No measures were taken to control the concrete temperature, resulting in a temperature of 32°C (89°F), significantly above the maximum limit of 24°C (75°F). The out-of-specification qualification batch was accepted in spite of the high concrete temperature. Strength tests using 100×200 mm (4×8 in.) cylinders from the qualification batch indicated a compressive strength of 35.1 MPa (5090 psi) at 15 days and an average 28-day strength of 39.5 MPa (5730 psi).

Qualification Slab – attempt 1 (7/12/2005). The first attempt at constructing the qualification slab was made on July 12, 2005. July air temperatures in Kansas regularly exceed 32°C (90°F). The placement was scheduled to begin in the morning (approximately 8:00 a.m.) when air temperatures are relatively low. Chilled water was used to control the concrete temperature but was insufficient to control the concrete temperature with the rapidly rising air temperatures. Air temperatures on 7/12/2005 ranged from 21° to 32°C (70° to 89°F), and had risen above 32°C (90°F) for the four days prior to the attempted placement. Using chilled water, the concrete supplier was not able to reduce the concrete temperature below 26°C (78° F). The placement was cancelled after two truckloads were rejected for not meeting temperature specifications. No concrete was placed.

Qualification Slab – attempt 2 (9/8/2005). The second attempt at constructing the qualification slab was successful on September 8, 2005, with construction starting at approximately 8:00 a.m. Air temperatures for the day ranged from 19º to 32ºC (67º to 90ºF).

The first truckload of concrete did not meet specifications for slump [185 mm (7.3 in.)] and was rejected, but the second truckload met all of the specifications and was accepted. The average slump for concrete placed in the qualification slab was 74 mm (2.9 in.), with a minimum of 55 mm (2.2 in.) and a maximum of 100 mm (4.0 in.). The average air content was 8.4%, with a minimum of 7.7% and a maximum of 9.2%. The concrete temperature ranged from 19º to 22ºC (66º to 72ºF), with an average of 20ºC (68ºF). Concrete cores were sent to Ash Grove Technical Center for testing air content and air void parameters. The test results indicated a very fine air void system with some bubble clustering. The average total air content in the four hardened concrete cores was 7.3% with a high of 9.9% and a low of 5.0%. The average entrained air content was 6.0%, and the average entrapped air content was

1.4%. Air-Void Analyzer (AVA) results on plastic concrete indicated a spacing factor of 0.226 mm (0.0105 in.), while the average spacing factor for the hardened concrete was smaller, at 0.074 mm (0.003 in.). The cores indicated that consolidation was adequate. Cores can provide evidence of whether double drum and single drum roller screeds work more paste to the surface and push coarse aggregate particles away from the deck surface. Photos of the cores did not indicate whether coarse aggregate particles were present near the top surface of the slab.

Concrete was placed using a conveyor belt with a drop of approximately 4.6 m (15 ft). Placement and finishing operations went smoothly, and the deck surface finished well with a single-drum roller screed. A bullfloat was used in spots. Three work bridges were used in addition to the finishing equipment bridge. The first bridge was used for bullfloating, and the fogging equipment was mounted on the back side of this work bridge. The fogging system consisted of 10 spray nozzles connected in series with flexible tubing and attached to the back of the first work bridge (Fig. 5.1). Both machine-mounted fogging and hand-held fogging were used. While in operation, the machine-mounted fogging equipment deposited water on the surface of the deck, and as a result the fogging was turned off. The second and third work bridges were used for burlap placement. The burlap was pre-placed on the work bridges before concrete arrived on site. The burlap was dropped onto the deck while the workers were standing or kneeling on the work bridges. Burlap placement was generally slow, with placing times ranging from 4 to 38 minutes, with an average of 21 minutes. The second layer of burlap was not placed immediately after the first layer, which slowed the operation because the workers needed to move the work bridges multiple times for each location. The only delay in finishing operations occurred due to a lag in concrete delivery.

On September 15, 2005 personnel from KDOT, Clarkson, and KU met to discuss the qualification slab and the upcoming placement. Clarkson felt that the mix finished well and that the fogging equipment put out too much water, so they planned to modify the equipment for the deck placement by closing or removing some of the nozzles.

Following the qualification slab, the contractor felt that the concrete could be pumped. On September 30, 2005, the contractor, at his own expense, demonstrated this by pumping 0.75 m^3 (1.0 yd^3) of the approved LC-HPC concrete.

Fig. 5.1 Fogging system depositing excessive water on the deck surface

Deck Placement 1 - South (10/14/2005). The first placement for LC-HPC-1 occurred in mid-October with construction starting at approximately 6:30 a.m. Air temperatures during the placement ranged from 11º to 15ºC (52º to 59ºF), with a minimum and maximum for the day of 8º and 24ºC (47º and 76ºF).

Concrete test results indicated that the slump ranged from 65 mm (2.6 in.) to 165 mm (6.5 in.) with an average of 96 mm (3.8 in.). Air contents ranged from 6% to 11.5% with an average of 7.9%. The concrete temperature ranged from 16ºC (61ºF) to 22ºC (72ºF) with an average of 20ºC (68ºF). The first concrete was tested before the pump, but subsequent concrete testing occurred primarily on the deck on samples obtained at the pump discharge. Only one truckload of concrete that did not meet specifications went into the deck at approximately Station 4+990, about 15 m (49 ft) past the east abutment. The air content for this truckload was 11.5% and the slump was 165 mm (6.5 in.).

The first placement of LC-HPC was pumped and it pumped well. A ramp was constructed to raise the back of the concrete trucks to facilitate the discharge of concrete into the pump truck. Placement was from east to west. Hand vibrators were used to consolidate the concrete in the first six feet of the deck (east end). Strike-off consisted of three passes with a single-drum roller screed and initially a pan drag over each section of concrete before advancing. Consolidation and strike-off operations proceeded without complication, except the pan drag was removed because it tore the finished concrete surface. After strike-off, bullfloating was necessary, but small voids remained in some locations. The largest of the voids were later filled with epoxy after all construction operations were completed. A new fogging system, different from the system used for the qualification slab, was mounted on the finishing bridge. Two spray nozzles were mounted to a platform, which was attached to the screed. The platform was approximately 0.9 m (3 ft) from the surface of the deck and the nozzles were aimed down toward the surface of the deck, as shown in Fig. 5.2. The equipment placed a water mist into the air but resulted in droplets falling onto the bridge surface. The pooled water was worked into the surface of the concrete by the bullfloating operation. It was decided that fogging, if used, should occur after bullfloating.

Significant effort in bullfloating (from the first work bridge) generally slowed the placement of the burlap. There was a 5 minute wait after the screed advanced while bullfloating was completed before burlap could be placed. Burlap was placed using the second and third access bridges. Burlap placement times ranged from 11 to 29 minutes with an average placement time of 16 minutes. The 10-minute limit for placement of the first layer of burlap was not met at any point on this placement.

Two sections of burlap with dry spots were placed on the deck 8.6 m (28 ft) from the east end, near a grouping of protruding reinforcing bars, which the plans describe as the base for a pedestrian signal. Once the dry spots were recognized, the

Fig. 5.2 Fogging system spraying water onto the deck surface, which was worked into the surface of the deck by the bullfloating operation – this practice increases the potential for cracking

contractor took corrective action by spraying the dry burlap with a hose. Thereafter, the workmen placed only fully wet burlap.

To keep the burlap wet, soaker hoses were placed immediately following burlap placement. Some sections were placed too early and resulted in indentions ("divots") in the deck surface due to the weight of the hoses and the flow of water on the plastic concrete. Three hoses were placed longitudinally along the length of the deck. When the burlap was removed after the curing period was completed, it was revealed that some areas of the deck were dry and the area of influence of the soaker hoses did not appear to cover the entire deck. These areas were scattered, but predominantly at the west end of the deck.

It was learned that the north-west corner of Placement 1 was uncovered during the 14-day curing period to facilitate work in preparation for casting the second placement. This section may have dried out during that time and before curing was resumed.

On October 28, 2008, KU personnel observed the removal of curing burlap and the application of the liquid curing membrane. The process began prior to sunrise and was completed after sunrise. The burlap was damp but not saturated, with portions that were fully dry when it was removed, as shown in Fig. 5.3(a), indicating that water had been turned off prior to removal, possibly the previous night. A large percentage of the concrete surface area was dry when the burlap was removed, as shown in Fig. 5.3(b). The surface of the concrete was rewet with a hose prior to applying the curing membrane.

The curing membrane was applied as the specifications indicated. The first coat was applied in sections approximately 4.6 m (15 ft) square, as shown in Fig. 5.4(a). When applying the second coat of membrane, the worker walked on the fresh (wet) first coat, as shown in Fig. 5.4(b). Walking on the fresh (wet) membrane potentially damages the curing membrane, as shown in Fig. 5.4(c). If the membrane is applied in sections that are narrow, such as 0.9 m (3 ft) by 4.6 m (15 ft) sections, then the second coat may be applied without walking on the first coat. The narrow application area allows for a worker to reach across the application area, properly applying the second coat of membrane (at right angles to the surface), without walking on the membrane at any time. Coverage was complete, but appeared somewhat uneven (Fig. 5.5) due to the overlap of application areas, seen as darker (thicker) stripes on the deck [Fig. 5.4(a) and (b)]. This is typical for liquid membranes applied with hand-held spraying devices.

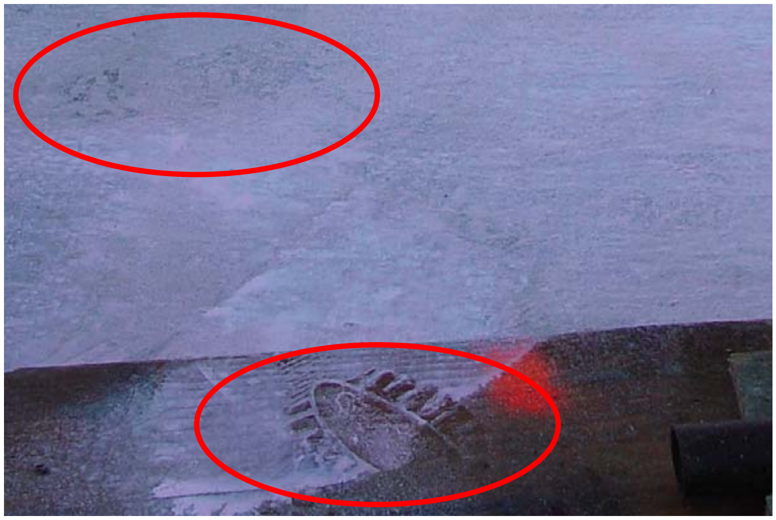
(a)

(b)

Fig. 5.3 Dry concrete surface when burlap was removed – does not meet specifications

Fig. 5.4 (a) Application of the first coat

Fig. 5.4 (b) Application of the second coat – worker damaging the first coat by walking on it



(c) Damage to wet curing membrane due to footprints

Fig. 5.4 Application of the liquid membrane – method caused damage to the first coat

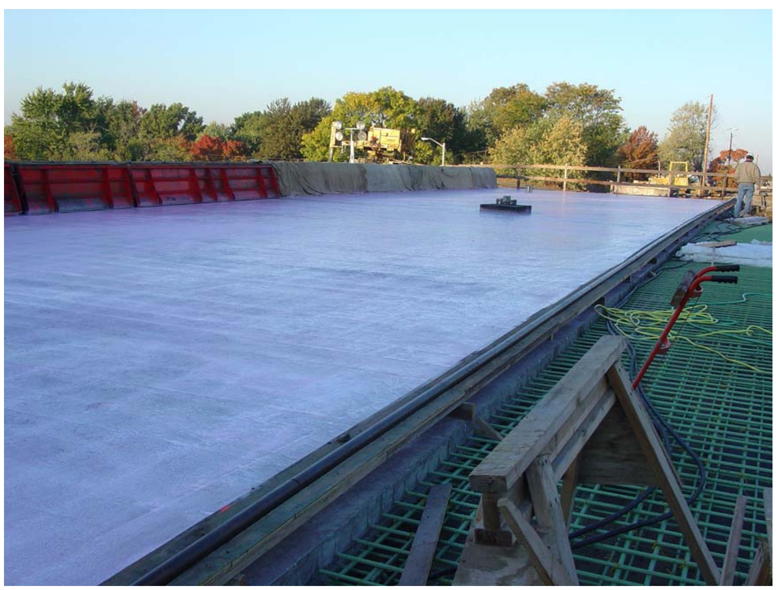


Fig. 5.5 Typical coverage of liquid membrane application appears uneven

Fig. 5.6 Divots observed in the deck surface

During the removal of the curing material and the application of the curing membrane some divots (caused by not finishing the deck completely smoothly due to stiff concrete) and some indentations (caused by the early placement of the soaker hoses) were observed in the deck surface as shown in Figs. 5.6.

The forms were removed from Placement 1 on days 5, 6, 10, 11 and 12 after the deck placement. Normally forms are not removed until after the curing period is completed. In this case, the Engineer allowed the contractor to remove the forms early to place lighting utility conduit on the underside of the deck. It is not clear whether flexural test specimens were made and tested (according to KDOT standard requirements) to allow the early removal of the forms.

Deck Placement 2 - North (11/2/2005). Placement was by pumping from east to west. The concrete was sampled after the pump, and the air loss through the pump was not established. Concrete test results indicated that the slump ranged from 64 mm (2.5 in.) to 108 mm (4.3 in.) with an average of 83 mm (3.3 in.), and only one truckload exceeded the maximum slump allowed. Air contents ranged from 3% to 9% with an average of 7.7%. One of the 10 truckloads tested (total of 26 truckloads for the placement) had an air content below 6.5%. The concrete temperature ranged from 19ºC (66ºF) to 21ºC (70ºF) with an average of 20ºC (68ºF). The concrete trucks discharged into the pump from a raised soil ramp.

Consolidation and strike-off operations proceeded without any complications. The concrete in the first 2.4 m (8 ft) of the deck was hand vibrated. The fogging equipment for Placement 2 was not the same as for Placement 1 or the Qualification Slab. The equipment was mounted on the single-drum roller screed, approximately 300 mm (12 in.) above the concrete surface with two spray nozzles directed downward, as shown in Fig. 5.7. The fogging equipment sprayed water on the surface of the concrete, which was used as a finishing aid. Significant amounts of paste were visible on the surface during bullfloating (Fig. 5.8) for approximately the first 4.6 m (15 ft) of the placement. The fogging was turned off after approximately 13.7 m (45 ft) of the deck had been finished. The finish was not as smooth at approximately 21.3 m (70 ft), so the contractor turned on the fogging at approximately 24.4 m (80 ft). The fogging was turned off and remained off at approximately 29.0 m (95 ft) because the contractor was working the fogging water into the surface of the deck with the bullfloating. This increases the paste content at the surface of the deck and makes it more prone to plastic shrinkage cracking and drying shrinkage cracking. The procedure that provided the best finish and did not work extra water in to the surface was to use no fogging (no application of water to the surface of the deck) and allow the finishers to use the bullfloat until the surface was adequately smooth. The finish was satisfactory, but for some areas it was not entirely smooth. Getting the wet burlap placed quickly is more important than obtaining a perfect finish. The finishing operation on Placement 2 was generally more thorough than for Placement 1 and resulted in a smoother surface.

Fig. 5.7 Fogging system mounted on roller screed and spraying water onto the concrete surface – this practice increases the potential for cracking

Fig. 5.8 Fogging system spraying water onto the deck surface and bullfloating working the water into the surface of the deck – this practice increases cracking

Burlap was placed using the first and second work bridges, a change from the first placement. The first work bridge was also used for bullfloating. Two workers opened and transferred burlap to 6 workers standing on the work bridges. The burlap was placed about 3 m (10 ft) behind the screed. Placement time after strike-off ranged from 7 to 17 minutes with an average time of 11 minutes. Fifty six percent of the stations timed along the deck met the 10-minute burlap placement requirement.

Finishing and burlap placement were delayed while the west abutment was filled with concrete. The exposed concrete [approximately 4.7 m (15 ft)] was not fogged during this delay.

The burlap tended to dry quickly. Soaker hoses were not placed on the plastic concrete for this placement because they had caused indentions in the first placement. Instead, the contractor kept the burlap wet using a garden hose with a spray nozzle, continually rewetting the entire area of the deck. This method worked well.

The air temperature dropped below freezing during days 13 and 14 of the curing period for Placement 2. No protection was provided to keep the concrete and girders above 4°C (40°F). The jersey barrier (attached to placement 1) was cast using LC-HPC material immediately following Placement 2.

The forms were removed from Placement 2 on days 29, 30, 49, 82 and 83 after the placement.

Unique Considerations. Though not required by the specifications, the jersey barrier for LC-HPC-1 was cast with the LC-HPC concrete, but was cured in accordance with standard KDOT methods.

The northwest corner of Placement 1 was uncovered during the curing period to facilitate work in preparation for casting Placement 2. This section may have dried out during that time.

The air temperature dropped below freezing during days 13 and 14 of the curing period for Placement 2. No protection was provided to keep the concrete and girders above 4°C (40°F).

Personnel Response and Post-Construction Conference. Representatives from KDOT, KU, the contractor, and the concrete supplier attended a post-construction conference to discuss the successes and difficulties for the placements. The responses and lessons learned from the experiences were documented and are summarized next.

The contractor liked the LC-HPC material. The bridge superintendent indicated that he preferred working with the optimized LC-HPC concrete, containing 320 kg/m^3 (539 lb/yd^3) of cement at 20ºC (68ºF), to the traditional mix containing 357 kg/m^3 (602 lb/yd^3) cement without temperature control.

The ready-mix concrete supplier indicated that obtaining the (granite) aggregate was the most challenging aspect of the project. He said the material was transported by railroad and there was an unavoidable delay in delivery even though they ordered the material (six weeks) in advance. The ready-mix concrete supplier also indicated that it is possible to pump concrete with 64-mm (2½-in.) slump.

LC-HPC-1 required significant spot grinding, therefore the KDOT construction engineer for the project suggested changing the specification to require grinding of the whole deck. Subsequentially, as discussed in Section 4.3.4, the third version of the construction special provision, 90M-7296, beginning with LC-HPC-8, and all subsequent versions require grinding of the entire deck surface. Further experience showed that it was unnecessary to grind the entire deck and not all subsequent LC-HPC decks were ground.

Lessons Learned. The LC-HPC concrete pumped well, even though the gradation did not meet the specification requirements on one sieve. A conveyor also transported the concrete easily without segregation.

Requiring the concrete to meet testing specifications prior to placement (during the qualification batch and slab, and testing trucks before placement in the deck) helps maintain tighter control of properties throughout the project.

Rejecting concrete that does not meet the specifications in the beginning of a project sends a message to the supplier and the contractor that the specifications must be followed.

After the burlap is placed and before the soaker hoses are placed, rewetting the burlap with a hand-held spray hose on an ongoing basis may be necessary to keep the burlap from drying out.

Hand fogging should be used during periods when the finishing operation is delayed.

Specifications should not require grinding of the entire deck surface.

A raised ramp for concrete discharge is helpful to get concrete out of the truck.

Fogging equipment should not deposit water on the deck.

Fogging should occur after the final finish has been completed.

To ensure the concrete does not dry out, consider requiring inspection when curing materials are removed and during the application of the curing compound.

5.3.2 Bridge LC-HPC-2

The first two LC-HPC bridge decks let in Kansas (LC-HPC-1 and LC-HPC-2) were in a single contract along with the control structure for both decks, Control 1/2. LC-HPC-2 is the bridge on 34th Street over I-635 in Kansas City, KS. The contract was awarded to W. A. Ellis Construction who subcontracted the bridges to Clarkson Construction. LC-HPC-2 was the third LC-HPC bridge deck constructed in Kansas, and was completed successfully on September 13, 2006. The dates related to the construction of LC-HPC-2 are shown in Table 5.2.

Design. The 34th Street over I-635 bridge is a two-span, steel girder (rolled beams) bridge with integral abutments and no skew. The bridge has relatively light traffic and is relatively narrow.

The LC-HPC deck is 12.20 m (40.0 ft) wide and 53.37 m (175.1 ft) long, with the actual driving surface being only 10.4 m (34.1 ft) wide. A sidewalk (not LC-HPC) was cast on top of the bridge deck and cantilevers out on each side of the deck 600 mm (2.0 ft). Corral rail style barriers separate the sidewalks from the driving surface portion of the deck and a fence barrier is located on the exterior portions of the sidewalk. Crack surveys for LC-HPC-2 are performed on the exposed driving surface portion of the bridge deck and do not include the sidewalks. LC-HPC-2 was constructed in one placement.

Table 5.2 – Construction Dates for LC-HPC-2

Item Constructed	Date Completed
Contract let	9/15/2004
Qualification Batch (Trial Batch)	6/23/2005
Qualification Slab (Trial Slab) for LC-HPC-2	5/24/2006
LC-HPC-2 Placement	9/13/2006
Post-Construction Meeting	2/20/2006

Concrete. Fordyce Concrete provided the concrete for the LC-HPC-1 and 2, with a haul distance of 13.0 km (8.1 mi) and an average haul time of 14 minutes for LC-HPC-2. The concrete mix design for both LC-HPC-1 and 2 included a cement content of 320 kg/m^3 (539 lb/yd^3), a *w/c* ratio of 0.45, and an air content of 8.0%. The aggregates included three granite coarse aggregates (SG 2.63), and one natural river sand fine aggregate (SG 2.61). The total aggregate gradation for the qualification batch and qualification slab was originally optimized, but, as with LC-HPC-1, the total aggregate gradation for the deck placement was not re-optimized for the "as-delivered" aggregate gradations. The actual gradation (as placed in the deck) was, also like LC-HPC-1, slightly out of specification (approximately 2% retained) on the 2.36-mm (No. 8) sieve. The small difference did not appear to affect the contractor's ability to handle, place and finish the concrete.

Qualification Batch. The qualification batch on 9/20/2005 was the same as for LC-HPC-1, discussed previously in Section 5.3.1.

Qualification Slab (5/24/2006). The qualification slab for LC-HPC-2 was placed on May 24, 2006. The evaporation rate at 9:05 a.m., approximately the time placement began, was estimated to be 0.02 lb/ft^2/hr. According to weather station records, air temperatures for the day ranged from 21º to 33ºC (70º to 91ºF).

The placement was scheduled to begin at 7:00 a.m., but the first truck was rejected for high slump. The first slump measurement was 190 mm (7.5 in.) and the retested value was 150 mm (6 in.) slump at 8:10 a.m. The concrete for LC-HPC-2 was batched with ice to control the concrete temperature, but for the first trucks an equal weight of water was not removed, effectively increasing the *w/c* ratio of the concrete. The second truck arrived at 8:46 a.m., with a slump of 100 mm (4 in.) and placement began at 9:20 a.m. The average slump for the three truckloads of concrete placed in the qualification slab was 117 mm (4.6 in.), above the specified maximum. Only one of the three truckloads had a slump of 100 mm (4.0 in.) and met specifications, the other trucks had slumps of 110 mm and 140 mm (4.3 in. and 5.5 in.). The average air content for the concrete was 7.8% air, with range of 7% to 8.5%. The concrete temperatures ranged from 19º to 22ºC (66º to 72ºF), with an average of 21ºC (70ºF). The cores indicated that consolidation was adequate and that coarse aggregate particles remained close to the upper surface of the deck with the current finishing technique using a single-drum roller screed.

Concrete was placed in the qualification slab using a pump, and placement, consolidation and finishing went smoothly. Fogging was not used because the humidity was high and the burlap placement proceeded quickly. Two work bridges were used to bullfloat the concrete and place burlap. The high-slump concrete finished easily with a single-drum roller screed and the bullfloating operation was minimal and quick. Bullfloating was performed from the first work bridge, immediately after strike-off and directly following the screed. The first work bridge followed the finishing bridge as close as physically possible, generally within 0.3 m (1 ft) of the finishing bridge. The support rail wheels for the finishing bridge and the first work bridge were often nearly touching. Burlap placement was within 10 minutes and 3.0 m (10 ft) of strike-off.

The burlap was presoaked and delivered to the qualification slab dripping wet. It was placed between the first and second work bridges in a timely fashion. Double layers of burlap were placed simultaneously. After it was placed, the burlap was immediately rewet with a hand-held spray hose by a worker standing on the second work bridge. The burlap placed over the guard rail reinforcing bars was initially tented out away from the reinforcing leaving several feet of concrete surface covered but not in contact with saturated burlap. Several locations also had gaps in the burlap, leaving concrete surfaces exposed to drying conditions. The contractor was notified that the burlap should be tucked in closely to the rail reinforcing and these items were corrected. The crews generally consisted of the same individuals as for previous LC-HPC placements by this contractor. They seemed to be comfortable with the procedures and efficient in placing the burlap.

The placement of the qualification slab went smoothly until the placement stopped approximately 1 m (3 ft) short because the contractor ran out of concrete. The concrete plant had begun to produce a different mix and the contractor said he couldn't order more. In retrospect, the contractor should have been required to fully complete the qualification slab.

Deck Placement (9/13/2006). The bridge deck was placed on September 13, 2006, with construction beginning at approximately 5:30 a.m. Air temperatures during the placement ranged from 13º to 21ºC (56º to 70ºF), with a minimum and maximum for the day of 9º to 27ºC (48º to 80ºF).

Concrete samples were obtained on the deck (after the pump). There was generally poor adherence to standardized testing procedures and good concreting practice during the testing of concrete properties. Improper testing procedures during the slump tests included incomplete consolidation, tilting the cone during the lift, jerking the cone prior to lift, and disposal of concrete samples into the deck forms 45 minutes prior to deck placement at that point, not testing the final three trucks; several trucks were not retested after re-mixing at the end of the placement. All of the five strength specimens were made from the first concrete discharged from the first truck.

Concrete test results indicated that the slump ranged from 33 mm (1.3 in.) to 100 mm (4.0 in.) with an average of 77 mm (3.0 in.). Visual inspection indicated that two trucks with approximately 150 mm (6.0 in.) slump were placed in the deck at about the half-way point. Air contents ranged from 7.0% to 8.5% with an average of 7.7%. Air loss through the pump was minimized with an air cuff attached to the discharge hose. Concrete temperature was controlled using chilled water and ice [24 kg/m^3 (40 lb/yd^3)]. Concrete temperature ranged from 16.1º to 20.6ºC (61º to 69ºF) with an average of 19.2ºC (67ºF). Surface temperatures of the concrete, as delivered, ranged from 16º to 21ºC (60º to 70ºF) with an average of 18.6ºC (65ºF) as measured with an infrared thermometer. The average surface temperature was 0.6ºC (2ºF) lower than the value obtained with a thermometer.

Deck placement went very smoothly, reflecting the experience of the contractor, as this was the contractor's fifth placement of LC-HPC. The direction of placement was from east to west. Concrete was placed with a pump and concrete trucks discharged into the pump from a soil ramp. Concrete with a slump of 33 mm (1.3 in.) was pumped without a problem. A single-drum roller screed followed by bullfloating was used to finish the concrete. Due to the reinforcing bar layout, the sidewalk portion of the deck was consolidated with hand held vibrators, as shown in Fig. 5.9.

Fig. 5.9 Consolidation of the sidewalk portion of the deck

Fogging was not used because the evaporation rates remained low. There were three delays in the finishing operations (11, 17, and 17 minutes) due to lack of concrete. One of the delays occurred during repositioning the only concrete pump to the opposite side of the bridge. At approximately two-thirds of the way through the placement (2/3 the length of the deck), the concrete in the deck was stiffer and the contractor was asked to float the concrete surface more to get a smoother surface. For the last 4.6 m (15 ft) of the deck the contractor sprayed water on the deck to make it easier to finish. This was stopped immediately.

The burlap was delivered by a crane on pallets directly onto the work bridges. Some of the burlap felt wet to the touch but had dry spots when it was laid out on the work bridges. A spray hose was used to rewet the burlap. In the same manner as used for the qualification slab, the burlap was loosely draped over the barrier reinforcement leaving gaps at the bottom where the burlap did not contact the surface of the deck (Fig. 5.10). Early in the placement, this was noticed, and the contractor was asked to reposition the burlap so that it contacted the entire surface of the deck and was tucked in close at the base of the reinforcing steel. Eleven crew members participated in the burlap placement, including: 1 operating the crane, 4 pushing the work bridges (one per bridge end), 1 wetting the burlap with a hose, 4 placing the burlap (2 per work bridge), and 1 reloading burlap at the crane. Two layers of burlap were placed simultaneously. The time to burlap placement ranged from 10 to 28 minutes with an average time to placement of 16 minutes for the 8 locations timed. Only one of the eight locations timed (13%) met the 10-minute specification requirement. Finishing and burlap placement operations were delayed for 12 minutes while the second (west) abutment was filled. The final 3.7 m (12 ft) of deck was unprotected and not fogged during this time.

Grinding was necessary, but it did not remove all of the surface imperfections.

The sidewalk was placemented on October 6, 2006. The corral rail was placed on October 11, 2006. The forms were removed on days 17, 19, 20, 50, 51 and 52 after placement.

Fig. 5.10 Burlap draped over reinforcement without contact at the base

Crack surveys show a significant amount of surface scaling in the form of cement paste pop-outs occurring at coarse aggregate locations in the north and south gutters of LC-HPC-2. This surface scaling was observed during the crack survey conducted approximately 7 months after construction.

Unique Considerations. The sidewalk for this bridge was cast (on 10/6/06) on top of the bridge deck outside of the barrier rail steel. The sidewalk is, therefore, not included in crack surveys.

Personnel Response and Post-Construction Conference. The contractor claimed to understand that he should not overfinish the deck with the bullfloat. It was explained that in trying to make the surface of stiff concrete smooth, he was not over-finishing the concrete, but that using water as a finishing aid would cause over-finishing problems.

The contractor informally requested to skip the qualification slab for the next bridges, contract Group 3, reasoning that his company had adequate experience. He was told to submit the request and it would be considered if the next bridge was placed within a reasonable time period, perhaps 5 to 7 months.

During the post-construction conference, the contractor stated that the concrete workability was excellent and even better than standard plasticized concrete mixtures. He also said that pumping worked well but he didn't like how it looked when it was finished. He indicated that a double drum screed may have helped to obtain a smoother finish.

It was generally agreed upon that the weather and evaporation conditions worked well for this (September) placement, but could cause problems if construction occurred during hot summer months. The fogging equipment did not work as intended.

Increases in the time to burlap placement rates corresponded with delays in concrete delivery.

The contractor stated that his bid prices have dropped significantly as they have gained experience and that the new special provisions caused the initially inflated prices.

Lessons Learned. Bid prices are dropping quickly as the contractor gains experience with LC-HPC construction.

Successful LC-HPC bridge deck placement is repeatable.

LC-HPC can be pumped.

Coarse aggregate particles can remain very close to the top surface of the deck when the deck is finished with a single drum roller screed.

5.3.3 Bridge Control 1/2

Control 1/2 was let in the same contract as bridges LC-HPC-1 and LC-HPC-2. Control 1/2 is the westbound (north) bridge on Parallel Parkway over I-635 in Kansas City, KS. LC-HPC-1 is the eastbound (south half) portion of the same bridge and is described earlier in Section 5.3.1. The contract was awarded to W. A. Ellis Construction who subcontracted the bridges to Clarkson Construction.

Dates related to the construction of Control 1/2 are shown in Table 5.3. Control 1/2 was constructed in four placements during the fall of 2005 (September and October) with a completion date of October 28, 2005.

Table 5.3 – Construction Dates for Control 1/2

Item Constructed	Date Completed
Subdeck Placement 1 (north half)	9/30/2005
Subdeck Placement 2 (south half)	10/18/2005
Silica Fume Overlay (SFO) Placement 1 (north half)	10/10/2005
Silica Fume Overlay (SFO) Placement 2 (south half)	10/28/2005

Design. The design of the Parallel Parkway over I-635 bridge is described in Section 5.3.1.

Control 1/2 is 47.30 m (155.2 ft) long with two spans with lengths of 23.27 m (77.6 ft). It is 20.75 m (74.6 ft) wide and was constructed in two placements. The north placement is 8.91 m (29.2 ft) wide and the south placement is 11.84 m (38.8 ft) wide.

The first placement for Control 1/2 was along the north edge of the bridge, and the second placement was directly to the south of the first placement and adjacent to LC-HPC-1. A Jersey barrier is located on the north edge of the first (north) placement. Much of the surface area for the first placement does not support traffic, but is open space containing traffic signals and curb barriers for traffic. The portions near each end of Placement 1 are used for exit/entrance ramp traffic from I-635. Most of the westbound traffic lane on Parallel Parkway is part of the second (south) placement of Control 1/2.

The top mat of reinforcing steel in the deck of Control 1/2 consists of No. 16 (No. 5) bars spaced at 150 mm (5.9 in.). The deck is designed to have 75 mm (3.0 in.) of top cover and 30 mm (1.2 in.) of bottom cover. The subdeck depth is 180 mm (7.1 in.) and the SFO depth is 40 mm (1.6 in.), for a total depth of 220 mm (8.7 in.).

Concrete. The concrete mix designs for both the subdeck and the SFO meet the KDOT specifications for this type of structure. The concrete mix for the subdeck was the standard KDOT mix, containing 357 kg/m^3 (602 lb/yd^3) of Type I/II cement for the north subdeck and 359 kg/m^3 (605 lb/yd^3) for the south subdeck, a *w/c* ratio of 0.40, and an air content of 6.5%. The aggregate used in the subdecks was a 50:50 blend of natural sand (BSG_{SSD} = 2.61) and limestone (BSG_{SSD} = 2.63). The silica fume overlay concrete included a 7% silica fume replacement of cement, or 26 kg/m^3 (44 lb/yd^3), a *w/cm* ratio of 0.37, and an air content of 6.5%. Granite (BSG_{SSD} = 2.63) from Arkansas was used as the coarse aggregate for the SFO.

Deck Placement. The deck placements were not observed and standard practices are assumed to have been used, including a 7-day curing period.

Construction of Control 1/2 occurred in four placements. The north subdeck was the first placement on September 30, 2005. The north SFO was placed next, on October 10, 2005. The south subdeck was placed on October 18, 2005 and the south SFO was placed on October 28, 2005.

Site condition reports indicate that environmental conditions and concrete temperatures created evaporation rates ranging from 0.1 to 0.6 kg/m^2/hr (0.02 to 0.12 lb/ft^2/hr) on three of the four placements, below the maximum limit of 1.0 kg/m^2/hr (0.2 lb/ft^2/hr), and therefore no measures to reduce the evaporation rate were required. The environmental conditions and evaporation rates for the south subdeck placement was not available from the construction diaries. Weather station data indicates that the daily high/low air temperatures for the four placements were 27º / 7ºC (80º / 45ºF) on September 30, 2005, 20º / 6ºC (68º / 42ºF) on October 10, 2005, 31º / 12ºC (87º / 53ºF) on October 18, 2005, and 21º / 1ºC (70º / 34ºF) on October 28, 2005.

5.3.4 LC-HPC Bridge 7

The second LC-HPC bridge deck constructed and the seventh LC-HPC deck let in Kansas (LC-HPC-7) is located on County Road 150 over US-75, approximately

15 minutes north of Topeka in Jackson county. The project was let to Koss Construction and the bridge was subcontracted to Capital Construction.

LC-HPC-7 was the second LC-HPC bridge deck constructed, with placement on June 24, 2006. Dates related to the construction of LC-HPC-7 are shown in Table 5.4.

Table 5.4 – Construction Dates for LC-HPC-7

Item Constructed	Date Completed
Qualification Batch (Trial Batch)	5/31/2006
Qualification Slab (Trial Slab) for LC-HPC-7	6/8/2006
LC-HPC-7 Placement	6/24/2006
Post-Construction Meeting	10/17/2006

Design. The County Road 150 over US-75 bridge is a two-span, steel plate girder bridge, which services low traffic volumes in rural Jackson County approximately 9.4 km (15 mi) north of Topeka, KS. It has integral abutments, jersey barriers, and no skew.

LC-HPC-7 is 85.00 m (278.8 ft) long with two span lengths of 42.5 m (139.4 ft) each. The total width of the LC-HPC deck is 16.65 m (54.6 ft), and it was constructed in one placement. The deck is monolithic with a total depth of 220 mm (8.7 in.), 75 mm (3 in.) of top cover, and 30 mm (1.2 in.) of bottom cover. Normally, LC-HPC decks have increased bottom cover because of the larger coarse aggregate. The bottom cover was not increased for LC-HPC-7, and the bottom cover is the standard bottom cover for conventional bridge decks in Kansas. There was no evidence of consolidation problems when the forms were stripped. The top mat of reinforcing steel consists of alternating No. 16 and 19 (No. 5 and 6) bars spaced at 160 mm (6.3 in.).

Concrete. Concrete Supply of Topeka provided the concrete for LC-HPC-7, with a haul distance of 31 km (19 mi). The concrete mix design for LC-HPC-7 was based on the design used for LC-HPC-1, except for the aggregate gradation and no water reducer was required to obtain the desired slump between 35 and 100 mm (1.5 and 4.0 in.). The cement content was held constant at 320 kg/m^3 (539 lb/yd^3), and three different *w/c* ratios (0.45, 0.43, and 0.41) were used during the project to adjust the workability. The qualification batch and the deck had a *w/c* ratio of 0.45, but the *w/c* ratio of the qualification slab concrete varied from 0.45, 0.43, and 0.41 so that the concrete supplier could make slump adjustments and provide flexibility if additional water was needed to increase the slump at the construction site. The design air content was 8.0%. The aggregates included two granite coarse aggregates (BSG_{SSD} = 2.64), and one natural river sand fine aggregate (BSG_{SSD} = 2.63). The concrete supplier used both ice and chilled water to control the temperature of the concrete. There were significant delays in the concrete supply both for the qualification slab and for the deck placement, resulting in slow finishing and burlap placement.

Qualification Batch (5/31/2006). The qualification batch for LC-HPC-7 was produced on May 31, 2006 at the Concrete Supply of Topeka plant in Topeka, Kansas with KU and KDOT representatives on site. Initially, the concrete supplier did not believe that ice would be needed to achieve the required concrete temperature. The supplier produced three trial batches before the concrete met specifications and was qualified. KDOT records indicate that the concrete contained 320 kg/m^3 (539 lb/yd^3) of cement and had a *w/c* ratio of 0.45, but during the qualification slab the concrete supplier indicated that to achieve the desired slump, the *w/c* ratio was adjusted to 0.40. Ice, at a rate of 37% replacement, was required to meet temperature specifications, but it did not require a water reducer or plasticizer to obtain the desired slump. The concrete met the specifications with an air content of 6.5%, a slump of 95 mm (3.75 in.), and a concrete temperature of 23°C (73°F). A full discussion of the qualification batching and the concrete challenges with LC-HPC-7 is discussed by Lindquist et al (2008).

Qualification Slab (6/8/2006). A preconstruction meeting was held at the construction site on June 7, 2006 to review the operations for the qualification slab, called a “trial slab” in this version of the specifications. The concrete temperature was a concern, as well as the *w/c* ratio of the mixture. It was decided to use a lower *w/c* ratio mixture and provide an “S-Hook” at the pump discharge to limit air loss through the pump.

The qualification slab for LC-HPC-7 was placed on June 28, 2006 next to the bridge site with placement beginning at approximately 5:20 a.m. and was completed by 7:10 a.m., for a total placement time of approximately 1.8 hours.

The concrete for the qualification slab met the specifications, but the delivery was often delayed and affected the rate of concrete placement, and finishing and placement of burlap. The average slump of the concrete placed in the qualification slab was 70 mm (2.75 in.), with a range of 50 mm (2.0 in.) to 85 mm (3.25 in.). The average air content was 8.5% with a minimum of 8.0% and a maximum of 9.0%. Full records for the concrete temperature are not available, but the first two truckloads had temperatures of 20º and 24ºC (68º to 75ºF), respectively.

Concrete was placed in the 15.9 m (52.1 ft) wide qualification slab with a pump. An “S-Hook” was attached to the end of the pump hose to reduce air loss through the pump. Placement operations were slow, with delays due to concrete supply and burlap placement. The wait times between trucks leaving and arriving on site were 11, 12, 27, and 24 minutes. This hurt the contractor’s ability to place, finish and cover the concrete.

Consolidation was performed by hand vibration for approximately the first and last 2.1 m (7 ft) of the qualification slab. Insertion points were typically at 46 cm (18 in.) centers for the hand-vibrators. The rest of the slab was consolidated using a gang-vibration system with 6 vibrators mounted on a separate work bridge in front of the finishing equipment. KDOT suggested that the contractor add several more vibrators to the gang-vibration system to reduce the number of insertion points for the wide bridge.

The concrete was finished using a double-drum roller screed with one roller removed and a pan drag. Because the concrete had a low slump and there were long delays between pumping and finishing, the contractor had difficulty finishing the slab, and there were some divots in the slab surface.

The fogging equipment consisted of four nozzles attached to the pan drag mount on the screed. They were mounted approximately 46 cm (18 in.) above the surface of the deck and pointed up. When the system was turned on, only two of the nozzles functioned, producing a fine spray fog as shown in Fig. 5.11. The system location was not desirable, so the contractor turned it off and instead used hand-held fogging from one side of the qualification slab. The contractor was told mount the fogging equipment on the finishing bridge for the deck placement. The hand-held fogging equipment contributed to water ponding on the surface of the finished deck, as shown in Fig. 5.12. Some water ponding on the placed burlap, and even on the deck, is acceptable if the water is not worked into the concrete surface.

Fig. 5.11 Fogging equipment mounted in an undesirable location on the pan drag close to the deck surface

Burlap placement was not efficient and there was difficulty in placing the burlap in a timely fashion. The required 10-minute time limit for burlap placement was not met at any station for the qualification slab. Three reasons contributed to the slowness of the burlap placement. First, the delays in concrete delivery from long wait times between truckloads caused delays in finishing and burlap placement. Secondly, only one work bridge was used to place burlap, slowing the process significantly. Finally, there were not enough workers placing burlap.

In general, the approach to the trial slab by the contractor and concrete supplier seemed to be to practice some of the techniques. Phrases such as “We’ll have that for the bridge” or “For the bridge we will…” were used several times. While the purpose of the trial (qualification) slab and the trial (qualification) batch are to practice, every effort should be made to produce concrete and the slab in accordance with all the specifications. Based on this experience, a change in terminology from “trial batch” and “trial slab” to “qualification batch” and “qualification slab” was made to communicate the importance of making every effort to place the slab fully in accordance with all of the specifications and to convey the understanding that the contractor may be required to repeat the slab if the performance is not satisfactory.

Fig. 5.12 Water ponding on deck surface due to hand fogging and burlap dripping on the surface. Using only one work bridge to place burlap is slow and did not meet the time requirements

At the end of the qualification slab, the KDOT construction engineer said, "Today proved the value of the trial [qualification] slab. We will be able to visually see how much the contractor learned from the beginning to the end of the trial slab."

A post-slab, pre-construction meeting was held on June 12, 2006 to discuss results of the qualification slab. It was clarified that only concrete that meets the specifications would be accepted, even for the abutments. During the qualification slab, concrete with a 50-mm (2-in.) slump pumped well. The contractor was instructed to have a second pump on site as a backup. The wait between truckloads during the qualification slab was not acceptable and caused most of the finishing problems, and the contractor did not meet the 10-minute burlap placement requirement. Two work bridges should be used for burlap placement and the contractor should keep the burlap wet with sprinklers, placing the soaker hoses as soon as possible. Rail work and form stripping were not allowed until the 14-day curing period was completed. In response to the question of whether the qualification slab was worthwhile, the contractor was unsure but the concrete supplier responded that it was worthwhile, especially for the concrete supplier to make the changes necessary and check how the air content changed through the pump. It was, however, difficult to see the benefit for finishing because of the delays in concrete supply.

Deck Placement (6/24/2006). The placement of LC-HPC-7 occurred on June 24, 2006, with construction starting at approximately 2:00 a.m. and ending at approximately 8:30 a.m. for a total time of 6.5 hours. The average placement rate for the placement was approximately 48 m^3/hr (63 yd^3/hr). Air temperatures during the placement ranged from 21º to 22ºC (70º to 71ºF), with minimum and maximum air temperatures for the day of 16º and 30ºC (60º and 86ºF) according to weather station data.

The LC-HPC-7 deck was cast with concrete that had a 0.45 *w/c* ratio. The KDOT concrete test records indicate that the slump ranged from 55 to 150 mm (2.25 to 6.0 in.) with an average of 95 mm (3.75 in.). Five truckloads had a slump that exceeded the specifications, ranging from 125 to 150 mm (5 to 6 in.). Air contents ranged from 6.5% to 10.5%, with an average of 8.0%. One truck had an air content of 10.5%, exceeding the maximum allowable air content. The concrete temperature ranged from 20º to 24ºC (68º to 75ºF) with an average of 23ºC (73ºF). Most of the difficulties with concrete delivery were addressed after the qualification slab. There was one delay at the end of the placement resulting in approximately 4.6 to 6.1 m (15 to 20 ft) of the deck located about 3 m (10 ft) from the west abutment left exposed for about 1 hour and 15 minutes. The evaporation rate was very low during this time, and the deck was not fogged or protected.

The low-slump concrete did not discharge easily through the truck chute into the pump truck. A dirt ramp was constructed for the concrete trucks to aid discharge. The KDOT inspector taking trip tickets and temperatures was an intern and did not have the experience to spot truckloads with high slump. This is an important job, and requires personnel that can pull a truck out for testing prior to discharge.

The placement of LC-HPC-7 was completed with some complications related to fogging and burlap placement. The concrete was placed using a pump with an "S-Hook" attached to the end of the discharge hose. Placement was from east to west, and US-75 highway was open to traffic during placement.

The concrete finished well with a double-drum roller screed with one roller removed, a pan drag, followed by a burlap drag attached to the screed. Bullfloating was needed to smooth the deck and was performed from a work bridge immediately following the burlap drag.

The fogging system was not adequate. It consisted of plastic nozzles attached to plastic piping, draped over the finishing equipment. Although it did produce a low volume of very fine fog, the system leaked and dripped, as shown in Fig. 5.13, and it was turned off. The evaporation rate was low, ranging from 0.10 kg/m^2/hr (0.02 lb/ft^2/hr) to 0.24 kg/m^2/hr (0.05 lb/ft^2/hr), and fogging was not used for the remainder of the placement.

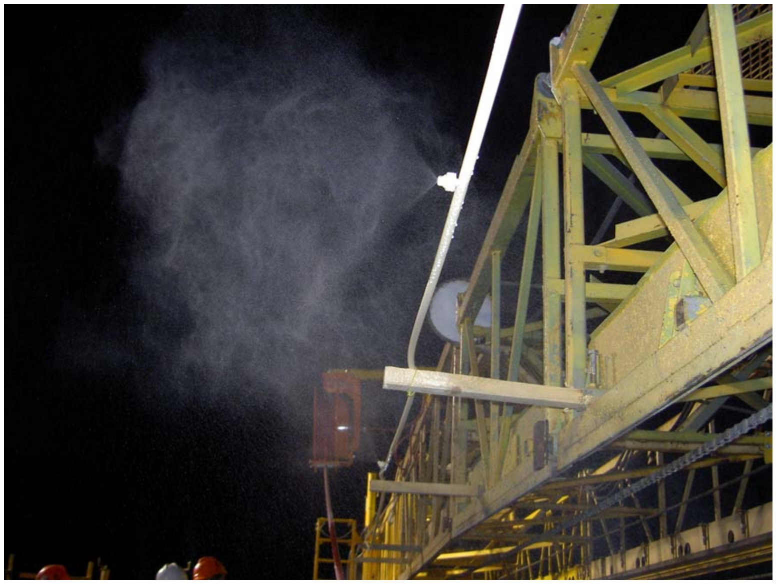


Fig. 5.13 Fogging equipment dripped when turned on and leaked when turned off

The crew placing the burlap was not the same crew as for the qualification slab, except for the supervisor. This was apparent in the beginning of the placement when the crew was taught how to place the burlap. This caused a significant delay in the burlap placement and the workers had to work hard to catch up with the finishing. The burlap placement was labor-intensive, inefficient, and slow. There were approximately 6 workers placing burlap and they became fatigued through the night, slowing the burlap placement. Presoaked burlap was carried by workers along the sides of the deck to the point of placement during the entire placement. Wet burlap is very heavy and should be lifted to the work bridges with a crane. The burlap was rolled and was often found to be twisted as it was unrolled, again slowing placement. Burlap should be folded rather than rolled to ease placement. The burlap was rewet on the work bridges before placement. For the three points along the deck that were timed, the time between finishing and burlap placement was 13, 11 and 7 minutes. As discussed previously, there was a delay in finishing and burlap placement at the end of the placement due to concrete delivery and filling the abutment. The delay in concrete delivery at the end of the placement was approximately 1 hour and 15 minutes for the concrete, and about 4.6 to 6.1 m (15 to 20 ft) of finished concrete remained exposed for nearly 90 minutes.

After it was placed, the burlap was kept wet with a sprinkler system and garden hoses. It worked well and kept the burlap wet, but resulted in too much water and runoff flowing from the deck. The contractor was instructed to turn off the sprinkler and to keep the burlap wet using only the hoses.

The average haul time from loading to discharge was 45 minutes, with a minimum time of 32 minutes and a maximum time of 120 minutes.

Forms were removed starting on day 11 after placement and removal was completed approximately a month later.

Personnel Response and Post-Construction Conference. A post-construction conference was held on October 17, 2006.

Because the concrete supplier had not initially believed they needed to use ice to control the concrete temperature, no plans had been made to load the trucks with ice. As a result, bags of ice were placed in the trucks from an elevated platform. Ice was carried to the platform using a ladder. Workers handling the ice walked off the job at about 3:00 a.m. during the deck placement. A conveyor belt has worked well on other LC-HPC decks placing ice into trucks.

The contractor indicated that once the concrete mix was correct, the placement and constructability of the deck was fine. He said that it was "not as bad as I thought."

The contractor indicated that the burlap placement requires more people than for a normal bridge deck.

KDOT personnel liked the qualification slab because it was an opportunity to resolve problems before the deck is placed. They said, "the deck is not the time to practice."

KDOT personnel indicated because three truckloads were rejected during construction of LC-HPC-1, everyone (contractor, concrete supplier, inspectors, KDOT personnel, etc.) understood that the project must conform to the specifications.

The bottom cover was not increased to account for the larger coarse aggregate. No pockets or shadow areas were found on the bottom of the deck. Increased cover may not be necessary for the larger coarse aggregate size.

KDOT and contractor personnel indicated that this deck did not require grinding. They didn't think that requiring grinding the entire deck surface was necessary.

Using a second pump to pre-fill the abutment can help to avoid delays at the end of the placement.

Unique Considerations. There was some concern by the contractor and KDOT that the volume of concrete placed in the deck was lower than expected based on the estimated volume, possibly indicating that not enough concrete was placed in the deck.

Lessons Learned. Rejecting trucks not only keeps substandard concrete out of the structure, but it also communicates to everyone that the specifications must be met. This influences future jobs as well.

Delays in concrete delivery can be significantly detrimental to placing, finishing, and covering of the concrete.

Ice can control concrete temperatures, but planning is important for successful handling during placement.

Considerable effort may be required in assisting the concrete supplier to produce and deliver concrete that meets specifications.

Consider removing the bottom mat of reinforcing steel from the qualification slab.

Use two work bridges to place burlap and transport wet burlap to the work bridges with a crane. Burlap placement requires more people than for a normal deck.

Grinding is not necessary for every deck.

Although it is recommended, increased bottom cover may not cause consolidation problems on the bottom of the deck.

Two pumps may be helpful in a wide deck placement and for pre-filling the final abutment to avoid delays at the end of a placement.

The names "trial slab" and "trial batch" were changed to "qualification slab" and "qualification batch" to communicate the importance of fully meeting the specifications for these items.

Exposed areas of the deck should be fogged with hand-held foggers during delays, particulary while the end abutment is being filled.

The inspector taking trip tickets should be experienced enough to spot trucks with high slump concrete and ask them to be tested before placing them in the deck.

5.3.5 Control Bridge 7

Control 7 is the northbound (east) bridge on Antioch over I-435 in Overland Park, KS. Control 7 was the only bridge in the contract and was awarded to Clarkson Construction Company. Dates related to the construction of Control 7 are shown in Table 5.5. Control 7 was constructed in four placements during 2006 with a completion date of September 15, 2006.

Table 5.5 – Construction Dates for Control 7

Item Constructed	Date Completed
Subdeck - placement 1 (east)	3/15/2006
Silica Fume Overlay (SFO) - placement 1 (east)	3/29/2006
Subdeck - placement 2 (west)	8/16/2006
Silica Fume Overlay (SFO) - placement 2 (west)	9/15/2006

Design. The northbound Antioch over I-436 bridge, sometimes referred to as the Antioch Bridge, is a two-span, steel plate-girder bridge with integral abutments, solid corral rails and a 3 degree skew. The construction of the Antioch bridge was completed in two stages. Stage 1 included the east portion of Control 7 (northbound) and consisted of 13.11 m (43.0 ft) of deck and 5 of 7 girders. Stage 2 included the southbound (west portion) bridge (not part of this study) and a small portion of Control 7, connecting Control 7 with the southbound bridge, including 5.79 m (19.0 ft) of deck and 2 girders of Control 7.

Control 7 is 58.8 m (192.9 ft) long. The two span lengths are 27.4 and 31.4 m (89.9 and 103.0 ft) long. The width of Control 7 is 18.9 m (62.0 ft). The Stage 1 portion of Control 7 is a 13.11-m (43.0-ft) wide placement, while the Stage 2 portion (west side) is 5.79 m (19.0 ft) wide.

The Control 7 deck has a silica fume overlay and a total depth of 220 mm (8.7 in.), 75 mm (3 in.) of top cover, and 30 mm (1.2 in.) of bottom cover. The subdeck is 180 mm (7.1 in.) thick and the silica fume overlay is 40 mm (1.6 in.) thick. The top mat of reinforcing steel consists of No. 16 (No. 5) bars spaced at 160 mm (6.3 in.).

Concrete. The concrete mix designs for the subdeck and SFO meet the KDOT specifications for this type of structure, modified to conform with the material requirements of Kansas City Metro Materials Board, as discussed in Section 4.2.3. The concrete for the subdeck consisted of a binary mixture containing 318 kg/m^3 (535 lb/yd^3) of Type I/II cement and 79 kg/m^3 (132 lb/yd^3) of Ashgrove Durapoz® F, a Class F fly ash blended with 15% sulfates (gypsum), a *w/cm* ratio of 0.40, and a design air content of 6.5%. The aggregate used in the subdecks was a 50:50 blend of natural sand (BSG_{SSD} = 2.61) and granite (BSG_{SSD} = 2.63). The silica fume overlay concrete included a 7% silica fume replacement of cement, or 26 kg/m^3 (44 lb/yd^3), 346 kg/m^3 (582 lb/yd^3) of Type I/II cement, a *w/cm* ratio of 0.37, and and air content of 6.5%. The granite was obtained from Arkansas.

Deck Placement. The deck placements were not observed and, except as noted, standard practices are assumed to have been used, including a 7-day curing period.

Construction of Control 7 occurred in four placements. For the Stage 1 construction, the east portion of the Control 7 subdeck was the first placement (on March 15, 2006). The east SFO was placed next, on March 29, 2006. For the Stage 2 construction, the west portion of the subdeck was placed on August 16, 2006, and the west SFO was placed on September 15, 2006.

KDOT records indicate that environmental conditions and concrete temperatures resulted in evaporation rates ranging from 0.28 to 0.35 kg/m^2/hr (0.06 to 0.07 lb/ft^2/hr) on three of the four placements, below the maximum limit of 1.0 kg/m^2/hr (0.2 lb/ft^2/hr), and therefore no measures to reduce the evaporation rate were required. Environmental conditions and the evaporation rate for the first SFO placement on 3/29/2006 were not available from the construction diaries. Weather station data indicates that the daily high/low air temperatures for the four placements were –2º / 14ºC (28º / 57ºF) on March 15, 2006, 3º / 12ºC (37º / 54ºF) on March 29, 2006, 16º / 31ºC (61º / 87ºF) on August 16, 2006, and 15º / 30ºC (59º / 86ºF) on September 15, 2006.

Unique Considerations. Upon request by KDOT, on October 18, 2006, KU personnel traveled to Control 7 for a site visit of Placement 1 to inspect reported cracking. KDOT construction personnel reported that for the second placement, the water truck supplying the curing water ran out of water overnight on the 1st night after placement and the burlap was found dry the next morning. Placement had been at night with lows of 15ºC (59ºF) and high temperatures of 32ºC (90ºF). Transverse cracks were observed on the surface of the deck in Placement 1 at approximately 2.4 m (8 ft) centers. Placement 2 was open to traffic and not available for observation. Cracking on the underside of the deck was also observed and documented. An analysis of the photos of the underside of the deck, shown in Fig. 5.14, indicated a crack density of approximately 0.4 m/m^2 for full depth transverse cracking on some regions of the deck, close to the average cracking for this type of construction in Kansas.

Fig. 5.14 Through-depth cracking on the underside of Control 7 deck.

5.3.6 LC-HPC Bridge 10

The eighth, ninth, and tenth LC-HPC bridge decks let in Kansas (LC-HPC-8, 9, and 10) were in a single contract and were subcontracted to two different contractors. LC-HPC-10 is the bridge on E 1800 Road over US-69, located 8 miles north of Pleasanton, Kansas on US-69 highway. The contract containing the three LC-HPC bridges was awarded to Koss Construction, and LC-HPC-8 and LC-HPC-10 were subcontracted to A. M. Cohron Construction. LC-HPC-10 was the fourth bridge constructed in Kansas, and was completed on May 17, 2007. The dates related to the construction of LC-HPC-10 are shown in Table 5.6.

Table 5.6 – Construction Dates for LC-HPC-10

Item Constructed	Date Completed
Qualification Batch	4/11/2007
Qualification Slab	4/26/2007
LC-HPC Deck	5/17/2007
Post-Construction Meeting	5/29/2007

Design. The E 1800 Rd over US-69 bridge, is a four span, precast-prestressed concrete girder bridge with integral abutments, corral rails, and a 21 degree skew. The bridge deck was constructed in a single placement.

The LC-HPC bridge is 102.1 m (334.9 ft) long, with span lengths of 22.5, 29.8, 29.8, and 19.1 m (73.8, 97.8, 97.8, and 62.3 ft). The total width of LC-HPC-10 is 10.6 m (30.1 ft).

The LC-HPC-10 deck is monolithic with a total depth of 210 mm (8.3 in.), 65 mm (2.6 in.) of top cover, and 35 mm (1.4 in.) of bottom cover. The top mat of reinforcing steel consists of No. 16 (No. 5) bars spaced at 170 mm (6.7 in.).

Concrete. O'Brien Ready-Mix provided the concrete for the LC-HPC-10 deck from a mobile ready-mix plant located about 17 km (10.5 mi) from the bridge.

The specifications for LC-HPC-10 required a maximum cement content of 317 kg/m^3 (535 lb/yd^3) and a *w/c* ratio of 0.42, for a total paste volume of 23.3%. The mixture contained four aggregates, including two granite coarse aggregates (BSG_{SSD} = 2.63) from Arkansas, and two natural river sand fine aggregates (BSG_{SSD} = 2.63). The three smallest aggregates were used in the corral rail concrete mixture.

Qualification Batch (4/11/2007). The qualification batch for LC-HPC-10 and LC-HPC-8 was produced on 4/11/2007 at the mobile ready-mix plant. The concrete contained 317 kg/m^3 (535 lb/yd^3) of cement and had a *w/c* ratio of 0.42. The concrete met the specifications with an air content of 8.6%, a slump of 44 mm (1.75 in.) and a concrete temperature of 15°C (59°F). The air temperature at the time of the qualification batch was 8°C (47°F) and no measures were taken to control the concrete temperature, but the supplier anticipated using ice to control the concrete temperature during the deck placement.

Qualification Slab (4/26/2007). The qualification slab for LC-HPC-10 was placed on April 26, 2007 at a farm with a haul time of about 15 minutes. Placement began at approximately 9:40 a.m. and was completed by 11:30, approximately 1.75 hours. According to weather station records, the air temperatures during the day ranged from -2° to 21° C (29° to 70°F). Conditions were wet and the ground was saturated.

The concrete met the specifications except for the third truck. The first two trucks had water held back at the plant, and some of the water was added back and remixed before testing. For the third truck, the slump was initially 68 mm (2.7 in.) and the pump operator claimed that it wouldn't pump. KU personnel were not present at the pump to verify that pumping had been attempted. However, the previous truck (Truck #2) had the same slump and pumped adequately. Plasticizer was added to the third truck and the retested on the slab with a slump measurement of 130 mm (5.1 in.). The air content and the temperature for this truckload met specifications. The average slump of the concrete placed in the qualification slab was 91 mm (3.6 in.), with one truck (truck #3) exceeding the specified maximum slump. The average air content was 8.7% with a minimum of 8.2% and a maximum of 9.2%. The concrete temperature ranged from 20º to 23ºC (68º to 73ºF) with an average of 21ºC (70ºF).

Concrete was placed in the qualification slab with a pump. Placement operations were slow, with most of the delays due to concrete supply. The concrete supplier indicated that they could produce a maximum of approximately 61 m^3/hr (80 yd^3/hr) for the deck, and the contractor indicated that, on average, they can usually progress about 15 to 18 m (50 to 60 ft) per hour while casting a deck.

Consolidation was performed by hand vibration for approximately the first 2.4 m (8 ft) of the slab. Insertion points were typically at 305 to 485 mm (12 to 18 in.) centers. The rest of the slab was consolidated using a manually operated gang-vibration system including four hand vibrators mounted on a frame on rollers, as shown in Fig. 5.15.

Fig. 5.15 Manually operated gang vibration system used on LC-HPC-10 qualification slab.

The concrete finished adequately with a single-drum roller screed and a pan drag. Initially the screed continued to run during delays in concrete delivery, so the concrete was subjected to approximately six passes with the screed. The importance of maintaining progress on the finishing and not overworking the surface was discussed with the contractor, and the rest of the slab was not overfinished. Bullfloating was performed from the side of the deck, not from a work bridge to produce the final finish.

Fig. 5.16 Fogging system with flexible pipe - dripped water onto the deck surface

The fogging equipment was mounted on the back side of the finishing bridge. The system consisted of flexible pipe connecting 6 spray nozzles and produced a significant amount of fine mist into the air. Water accumulated on the surface of the equipment due to the mist and dripped onto the concrete surface (Fig. 5.16), especially after the water was turned off. The fogging was turned off early in the placement and not used for the rest of the day. During placement, there was some ponding on the surface of the finished concrete, possibly due to the saturated subgrade conditions. Simulated rail reinforcement was not present for the qualification slab.

Behind the finishing bridge, one work bridge was used to roll out the wet burlap and a second work bridge was also used to place the burlap. There was some difficulty in the burlap placement because the burlap was rolled and appeared awkward to handle on the very narrow work bridges. The burlap was folded in half (length wise) to provide two layers using one piece, and did not overlap at a few locations, leaving thin areas of finished concrete exposed between pieces of burlap. The contractor corrected this so that the burlap overlapped between sections and the whole slab was covered. At our suggestion, the contractor said that for the bridge placement they intended to fold the burlap accordion-style and transport the burlap to the work bridges with a crane. After the first truck, the average time to burlap placement was 7 minutes, with a maximum time of 8 minutes for the locations timed along the slab.

At the end of the placement, the contractor and KU discussed observations from the placement. There was some tension because this was the first experience with placement of LC-HPC by this contractor. In general, the contractor and the KDOT inspector were pleased with the concrete. The contractor indicated that the qualification slab is a good idea, but it is too short to get the effect of a real bridge deck.

Photos of the cores obtained from the qualification slab indicate that large coarse aggregate particles remain at or near the surface of the deck, as shown in Fig. 5.17.

Deck Placement (5/17/2007). The placement of LC-HPC-10 occurred on May 17, 2007 with construction starting at approximately 3:15 a.m. The last burlap

Fig. 5.17 – Cores from LC-HPC-10 qualification slab show coarse aggregate particles at or near the finished surface of the slab.

was placed at 12:15 p.m., for a total time of 9 hours. Placement was from east to west. A total of 357 m^3 (468 yd^3) concrete were placed, making the average rate for the placement 40 m^3/hr (52 yd^3/hr). Air temperatures during placement ranged from 11º to 22ºC (52º to 72ºF), with a minimum and maximum for the day of 8º and 21ºC (47º and 69ºF) according to weather station data. Air temperatures dropped to or below freezing on days 5, 9, and 10 of the 14-day curing period, and below 4ºC (40ºF) on 10 of the 14 days.

There was some difficulty achieving proper air contents for the first seven truckloads of concrete. Official KDOT concrete test records for the concrete placed in the deck (not the abutments) indicate that the slump ranged from 55 to 105 mm (2.25 to 4.1 in.) with an average of 80 mm (3.1 in.). Air contents ranged from 6.1% to 9.1% with an average of 7.5%. Concrete temperature ranged from 16º to 22ºC (60º to 72ºF) with an average of 18.3ºC (65ºF). Although the qualified mixture was designed with a *w/c* ratio of 0.42, the specifications allowed as much as 10 L/m^3 (2 gal/yd^3) to be withheld at the plant and added back as necessary. This resulted in water content adjustments on site for nearly every truck, and the *w/c* ratio of placed concrete ranged from 0.40 to 0.42 with an average *w/c* ratio for the placement of 0.41.

The first truck was adjusted by adding withheld water to raise the *w/c* ratio to 0.42. The first truckload had low air (5.5%) but was accepted because it was placed in the abutment. The second truck was adjusted by adding air entraining agent to increase the air content. The air increased from 4.9% to just 5.1%, but the concrete was accepted and the concrete was placed in the abutment. The third truckload had a slump of 125 mm (5 in.) and an air content of 11.0%. It was set aside to spin for 20 minutes then retested. The air content after waiting was 8.0% (the slump was not retested), and the concrete was accepted and placed in the abutment. The fourth truckload met all specifications. For the concrete placed in the deck, one truckload initially had a slump of 125 mm (5 in.) and was held out for the slump to drop and was not retested. Only one truck that was placed in the deck had a slump exceeding the specifications, and it had a slump of 105 mm (4.1 in.). Two truckloads were placed in the deck with air contents below the specified minimum. Concrete testing was performed on concrete sampled after it was deposited on the deck by the pump. There were no delays in concrete delivery throughout the placement.

The placement of LC-HPC-10 did not go smoothly. The pump worked adequately for most of the placement, but became clogged at the west pier cap. An unknown quantity of water was added to clear the pump, and the concrete was placed in the pier cap, not in the deck. Concrete was consolidated from a work bridge in front of the finishing screed and workers walked through the consolidated concrete to move concrete around in front of the screed.

The concrete was finished using a single-drum roller screed and a pan drag attached to the screed. Bullfloating was performed only at the beginning of the placement, whereas bullfloating had been performed on all of the qualification slab. The rate of finishing was slow and was the cause of most of the delays and was the overall limiting factor for the speed of placement of the deck. Delays also occurred when filling the pier caps, which were integral with the deck. To address this problem, later in the placement the pier caps were filled ahead of the slab. This was possible because the finishing equipment was moving slowly. The second half of the deck was harder to finish, requiring some hand finishing of the deck surface from the work bridges.

The fogging system did not work well. The machine-mounted equipment with flexible tubing leaked onto the deck and was turned off. Hand held fogging equipment was used intermittently during delays and was used to spray the surface of the concrete to aid finishing near the 3rd pier cap. This was stopped. The fogging and burlap operations were understaffed, and no one was assigned the task of fogging. The seven workers responsible for placing burlap and keeping the burlap wet were also responsible for fogging, and this resulted in a lack of attention for fogging. At one point, workers propped up the hand-held fogging equipment to spray the deck and left to do another job. This was stopped. The recorded evaporation rate during construction was 0.24 kg/m^2/hr (0.05 lb/ft^2/hr).

Much of the burlap dried out during the placement. Prior to placing the burlap on the deck, it was submerged in water for only a couple minutes prior to being lifted by crane onto the deck. The burlap was, therefore, not saturated and needed to be rewetted frequently after placement. There were problems with the rewetting procedure also. Workers initially used a hose with no spray nozzle to rewet the in-place burlap, resulting in water ponding on the deck surface. Several attempts were made to communicate the goal of spraying the entire surface enough to keep the burlap wet but not to pond water. Some areas of the deck were rewetted, but much of the burlap on the deck dried and was not rewetted properly.

Two layers of burlap were placed at the same time. There were locations left exposed because the edges did not overlap. Initially the burlap was placed around, not over, the barrier steel leaving the concrete under the barrier steel exposed. This was later corrected, and the barrier steel was covered.

The average time between finishing and burlap placement was 17 minutes, with a minimum time of 6 minutes and a maximum time of 41 minutes. At 12 of 19 (63%) locations, the time to placement of the burlap exceeded the 10 minute requirement, with times ranging from 15 to 41 minutes. A delay in finishing and burlap placement occurred while the pump was moved from the east to the west side of the bridge. Another delay occurred while the final abutment was filled and concrete was backordered.

The average haul time from loading to discharge was 41 minutes, with an minimum time of 25 minutes and a maximum time of 1 hour and 55 minutes.

No form removal dates were received from KDOT for LC-HPC-10, but the forms stayed in place for several months.

Unique Considerations. The prestressed concrete girders and integral pier caps caused some delays in concrete finishing. This is one of only two LC-HPC bridges with prestressed concrete girders.

Lessons Learned. When burlap is placed in double layers so that the edges do not overlap, areas of the deck (or slab) may be left exposed and unprotected. Placement of a single layer of burlap followed by separate placement of the second layer of burlap offset from the first is preferable. This removes the chance of unprotected concrete between sections of burlap.

At the qualification slab, the contractor and the KDOT inspector were pleased with the concrete. The contractor indicated that the qualification slab is a good idea but it is too short to get the effect of a real bridge deck.

During the bridge, it was clear that a minimum of three inspectors should be present observing 1) the concrete delivery and testing, 2) consolidation, finishing, and 3) fogging and placement of the burlap.

Delays in finishing may be avoided by prefilling the pier caps ahead of the finishing equipment.

When it's bad, it's all bad.

5.3.7 LC-HPC Bridge 8

LC-HPC bridge 8 was part of the same contract as LC-HPC-9 and 10. LC-HPC-8 is the bridge on E 1350 Road over US-69, located 3 miles north of Pleasanton, Kansas on US-69 highway. The contract was awarded to Koss Construction, and LC-

HPC-8 was subcontracted to A. M. Cohron Construction. LC-HPC-8 was the seventh bridge constructed in Kansas, and was completed on October 3, 2007. The dates related to the construction of LC-HPC-8 are shown in Table 5.7.

Table 5.7 – Construction Dates for LC-HPC-8

Item Constructed	Date Completed
Qualification Batch	4/11/2007
Qualification Slab	9/26/2007
LC-HPC Deck	10/3/2007
Post-Construction Teleconference	10/22/2007

Design. The E 1350 Road over US-69 Highway Bridge is a four-span, precast-prestressed concrete girder bridge with integral abutments, corral rails, and no skew. The bridge has four spans and was constructed in a single phase. The bridge is 92.4 m (303.0 ft) long with the four span lengths of 18.0 m (59.1 ft), 27.8 m (91.2 m), 27.8 m (91.2 ft), and 18.0 m (59.1 ft) long.

The total width of the bridge is 11.6 m (30.1 ft). The LC-HPC-8 deck is monolithic with a total depth of 210 mm (8.3 in.), 75 mm (3 in.) of top cover, and 35 mm (1.4 in.) of bottom cover. The top mat of reinforcing steel consists of No. 16 (No. 5) bars spaced at 170 mm (6.7 in.).

Concrete. O'Brien Ready-Mix provided the concrete for the LC-HPC-8 deck from the same mobile ready-mix plant used for LC-HPC-10, approximately 8 km (5 mi) from LC-HPC-8. The average time from loading to discharge for the deck was 25 minutes, with a maximum time of 33 minutes and a minimum time of 18 minutes.

The concrete used for LC-HPC-8 was the same as for LC-HPC-10. Details are provided in Section 5.3.6.

Qualification Batch (4/11/2007). The qualification batch for LC-HPC-10 and LC-HPC-8 was produced on 4/11/2007 at the mobile ready-mix plant. Details are provided in Section 5.3.6.

Qualification Slab (9/26/2007). A qualification slab was required for LC-HPC-8. The qualification slab was not waived because of the difficulties involved with the placement of LC-HPC-10. The qualification slab for LC-HPC-8 was completed on September 26, 2007 at a location next to the bridge. Placement began at approximately 8:00 a.m. and was completed by approximately 10:00 a.m., approximately 2 hours. According to weather station records, the air temperatures for the day ranged from 11° to 22° C (52° to 72°F). The ground within the slab forms contained some ponded water before placement. Simulated handrails were constructed for the qualification slab, but no rail reinforcement was included in the slab.

The concrete supplier initially held back water from first truckload of concrete and the air content was low. The water was added back, and the concrete was redosed with air entraining agent. Trucks 2 and 4 met specifications, but there are no test results recorded for truck 3. During this placement, concrete samples were tested before and after the pump, which indicated an air loss of 1%. The average slump of the concrete placed in the qualification slab was 45 mm (1.75 in.). The average air content (tested after the pump) was 7.0% with a minimum of 4.0% (the first truckload) and a maximum of 8.7%. The concrete temperature ranged from 18º to 19ºC (65º to 66ºF) with an average of 19ºC (66ºF).

Concrete was placed in the qualification slab using a pump with an "S-Hook" at the end of the hose. Consolidation was provided using the manually operated gang vibration system used for LC-HPC-10 (see Section 5.3.6). Finishing was completed with a single-drum roller screed and a pan drag, followed by bullfloating performed from a work bridge. Early in the placement, the screed required some maintenance.

The fogging system consisted of 10 spray nozzles connected with solid pipe. The nozzles were directed up and were approximately 1.1 m (3.5 ft) above the surface of the deck. The equipment deposited a large amount of water onto the surface of the concrete as shown in Fig. 5.18. The water was worked into the surface of the slab with the bullfloat, as shown in Fig. 5.19. The system was pressurized to 2.75 MPa

(400 psi), which was determined to be too low to properly atomize the water. The fogging system was turned off and water subsequentially dripped onto the concrete. The contractor was required to requalify the fogging equipment, preferably at a higher pressure, prior to placement of the deck.

Fig 5.18. Excessive surface water deposited onto the deck by the fogging.

Behind the finishing bridge, one work bridge was used to roll out the wet burlap and a second work bridge was used in conjunction with the first to place the burlap. The burlap was very dry and was rewet on the work bridge with a spray hose. The workers did not appear to know what to do for the burlap placement, even though a Cohron supervisor said they had practiced the day before. The workers needed to be instructed (with active participation by KU personnel) what to do, to get on the work bridges, to place two layers, and to do it quickly to meet the 10-minute time limit. There were large holes in the burlap. Cohron said they would have better burlap for the bridge deck.

Fig. 5.19. Water from fogging used as finishing aid – increases the potential for cracking

The time to burlap placement was checked at three locations along the slab. The individual times to burlap placement were 12, 16, and 7 minutes, with an average time to burlap placement of 12 minutes.

There was a teleconference on October 1, 2007 to discuss the results of the qualification slab. The following items were discussed:

1. Fogging. Cohron indicated that they were testing the fogging system with new nozzle sizes and at 1000 psi. A KDOT inspector was going to prequalify the new system that day. The fogging system would also be checked the day the deck was to be constructed before any concrete was placed.
2. Burlap. Cohron was presoaking the burlap and wrapping the saturated burlap with plastic. On the morning of the placement, they planned to open the plastic and rewet the burlap.
3. A KDOT inspector was going to prequalify the burlap the day before the deck placement for the condition, quantity, and degree of saturation.
4. Concrete would be pre-placed in the diaphragms to avoid delays in the deck placement.

5. Two pump trucks would be used.

Deck Placement (10/3/2007). The placement of LC-HPC-8 occurred on October 3, 2007 with construction starting at approximately 7:30 a.m. The last burlap was placed at 2:45 p.m., for a total time of just over 7 hours. Placement was from west to east. A total of 337 m^3 (442 yd^3) concrete were placed, making the average rate for the placement 46.5 m^3/hr (61 yd^3/hr). Air temperatures during placement ranged from 8º to 27ºC (47º to 80ºF), with a minimum and maximum for the day of 8º and 28ºC (46º and 83ºF) according to weather station data. Air temperatures dropped below 4ºC (40ºF) on day 8 of the initial 14-day curing period.

The concrete supplier was able to supply concrete that met the specifications with minimal delays. The specifications allowed the supplier to hold out water and add it back at the jobsite to adjust workability, and the *w/c* ratio varied, generally increasing, throughout the placement. Future versions of the specifications require that all of the water be added at the ready mix plant. The concrete is discussed in detail by Lindquist et al. (2008).

For LC-HPC-8, the concrete test results indicate that the slump ranged from 35 to 85 mm (1.5 to 3.25 in.) with an average of 54 mm (2.1 in.). The air contents ranged from 5.7% to 10.2% with an average of 8.0%, and the concrete temperature ranged from 15º to 23ºC (59º to 73ºF) with an average of 19ºC (67ºF). All of the truckloads met the specifications for slump, but four truckloads were placed in the deck that did not meet the specifications for air content, having air contents of 5.7%, 9.8%, 10.2%, and 9.7%. There were minimal delays of 2-3 minutes in the concrete delivery throughout the placement due to traffic control in the construction zone. The last truckload was backordered and caused a delay of approximately 30 minutes. The concrete temperature rose throughout construction, so adjustments were made to the percent of water replacement with ice to maintain concrete temperatures. Ice replacements of 27%, 36%, and 45% were used.

The placement of LC-HPC-8 went very well. At the time, this was the fourth LC-HPC placement by Cohron. The extra practice during the qualification slab (the second qualification slab for the contract) and extra effort communicating with the contractor regarding the specification requirements resulted in significant improvement in successfully completing the deck as compared with the construction of the LC-HPC-10 deck.

Concrete was placed in the deck using two pumps, one positioned on each end of the bridge to avoid a delays from moving the pump truck. Diaphragms and the final abutment were filled in three layers, with the first layer filled approximately 6 m (20 ft) in front of the finishing equipment, the second layer at approximately 3 m (10 ft), and the final layer filled along with the deck. This worked well and minimized delays in deck finishing and burlap placement.

Two sets of manually operated gang vibrators were used for this placement. The two sets were mounted on the same work bridge, which was placed in front of the finishing equipment. Workers walked in the consolidated concrete between the gang vibrators and the screed to move concrete in front of the screed.

The concrete finished well with a single-drum roller screed and a pan drag attached to the screed. Bullfloating was performed only in a few locations, where the concrete was a little stiff, and did not delay placement of the burlap.

For most of the day, fogging was not used because the burlap was placed relatively quickly. The maximum evaporation rate was 0.39 kg/m^2/hr (0.08 lb/ft^2/hr). The fogging system consisted of No. 4 nozzles (pointed up) connected with solid pipe. The system operated with a pressure of 7.24 MPa (1050 psi) and did an excellent job of creating a lot of mist without depositing water on the deck. The fogging was turned on at the end of the deck while waiting for the final load of backordered concrete. The foggers were on for about 10 minutes of the 20 minute delay. They did not deposit water on the surface of the deck but provided a fog mist in the air shown in Fig. 5.20.

Fig. 5.20 Fog misting the air over the deck without depositing water onto the surface of the deck during a delay in concrete placement

Placing the burlap went well but was on average a little slower than the 10 minute requirement. The burlap was presoaked and lifted onto the work bridges by crane. A crew of five workers and a supervisor placed the burlap on the deck. They generally placed the burlap within 3.0 to 4.6 m (10 to 15 ft) behind the finishing equipment, and sometimes as close as 0.6 m (2 ft). A single layer of burlap was placed first, then a second layer with the edges overlapping so that no concrete was exposed. For the most part, long pieces of burlap were used, reaching the entire width of the deck. The long pieces were more efficient to place than the shorter pieces, which required two pieces to cover the entire width. The workers did a good job of rewetting the burlap with a hand-held spray hose after placement. Having a supervisor working constantly with the burlap crew was key to the success of the burlap placement because the supervisor kept the crew working quickly and reminded them to rewet the burlap after placement. During the last portion of the deck placement, the burlap placement crew was very tired and slowed down. It may have been good to have one or two additional workers assigned to help with burlap placement, or to rotate workers to prevent the crew from becoming fatigued. A worker should be dedicated to rewetting the burlap. By the time the deck was completed, soaker hoses had been placed on the first third of the deck to keep the burlap wet.

The average time between finishing and burlap placement was 12 minutes, with a minimum time of 4 minutes and a maximum time of 27 minutes. Seventeen of 32 (53%) locations timed exceeded the 10 minute requirement, with times ranging from 11 to 27 minutes. Some of these times corresponded with filling the diaphragms and the final abutment, delays in concrete delivery, changing the pump, and waiting for backordered concrete.

The average haul time from loading to discharge was 25 minutes, with an minimum time of 18 minutes and a maximum time of 35 minutes.

No form removal dates were received from KDOT for LC-HPC-8, but it is understood that the forms stayed in place several months after the deck was placed.

Unique Considerations. The abutment and the integral pier caps were pre-filled ahead of the finishing equipment to minimize delays in concrete finishing.

Lessons Learned. Prefilling the diaphragms and the abutment can help reduce the delays in finishing the deck.

Placement of the burlap in single layers with the edges overlapping helps to ensure no concrete is left exposed. Having a supervisor continually work with the burlap placement crew helps to keep the burlap be placed quickly and keep the burlap wet. Rotation of crew members for burlap placement should help to prevent fatigue.

5.3.8 Control Bridge 8/10

Control 8/10 is the bridge on K-52 over US-69, 6 miles north of Pleasanton, KS on US-69. Control 8/10 was let in the same contract as bridges LC-HPC-8, 9, 10, and Control 9. The contract was awarded to Koss Construction, and Control 8/10 was subcontracted to A. M. Cohron Construction.

Dates related to the construction of Control 8/10 are shown in Table 5.8. Control 8/10 was constructed in a single phase with a completion date of April 16, 2007.

Table 5.8 – Construction Dates for Control 8/10

Item Constructed	Date Completed
Monolithic deck placement	4/16/2007

Design. The K-52 over US-69 Highway Bridge is a four-span, prestressed concrete girder bridge with integral abutments, corral rails, and no skew. Control 8/10 is 96.85 m (317.7 ft) long with four spans with lengths of 22.0, 27.8, 27.8, and 18.5 m (72.2, 91.2, 91.2, and 60.7 ft), and is 22.9 m (75.1 ft) wide.

The top mat of reinforcing steel in the deck of Control 8/10 consists of No. 16 (No. 5) bars spaced at 170 mm (6.7 in.). The monolithic deck has a total depth of 210 mm (8.3 in.), with 65 mm (2.6 in.) of top cover and 30 mm (1.2 in.) of bottom cover.

Concrete. The concrete mix design for both the monolithic deck meet the KDOT specifications for this type of structure. The concrete mix for the deck contained 363 kg/m^3 (611 lb/yd^3) of Type I/II cement, which is 6 kg/m^3 (9 lb/yd^3) more than the standard KDOT subdeck mix which contains 357 kg/m^3 (602 lb/yd^3) of cement. The concrete has a *w/c* ratio of 0.40 and contains 6.5% entrained air. The aggregate used in the deck was a 50:50 blend of natural sand (BSG_{SSD} = 2.62) and limestone (BSG_{SSD} = 2.60).

Deck Placement (4/16/2007). The deck placements were not observed and standard practices are assumed to have been used, including a 7-day curing period.

The deck placement was completed on April 16, 2007. KDOT concrete testing records indicate that the average slump was 137 mm (5.4 in.) with a minimum of 100 mm (4 in.) and a maximum of 200 mm (8 in.). The average air content was 7.4% with a minimum of 6.0% and a maximum of 9.5%. The deck was placed with a pump and the placement took approximately 7 hours. The average haul time, or time from loading to truck discharge, was 31 minutes, with a minimum haul time of 20 minutes and a maximum haul time of 50 minutes.

The air temperature during placement ranged from 19º to 23ºC (67º to 73ºF). Wind and evaporation rate information were not obtained from construction diaries. Weather station data indicates that the daily high/low air temperatures for the placement was 18º / 3ºC (64º / 38ºF), and that air temperatures did not drop below 4ºC (40ºF) during the 7-day curing period.

5.3.9 LC-HPC Bridge 9

LC-HPC-9 is the northbound bridge on US-69 over the Marais Des Cygnes River, 6.4 km (4 mi) north of Pleasanton, KS on US-69. Control 9 is the southbound companion bridge at the same location. LC-HPC-9 and Control 9 were let in the same contract as bridges LC-HPC-8, 10, and Control 8/10 to Koss Construction, and LC-HPC-9 and Control 9 were subcontracted to United Construction.

LC-HPC-9 was the fourteenth LC-HPC bridge constructed in Kansas and was completed on April 15, 2009. Dates related to the construction of LC-HPC-9 are shown in Table 5.9.

Table 5.9 – Construction Dates for LC-HPC-9

Item Constructed	Date Completed
Qualification Batch	3/25/2009
Qualification Slab – attempt 1	3/23/2009
Qualification Slab – attempt 2	3/25/2009
Qualification Slab – attempt 3; Meeting	4/1/2009
LC-HPC Deck Placement	4/15/2009
Post-Construction Meeting	6/3/2009

Design. The northbound US-69 over the Marais Des Cygnes River Bridge is a three-span, steel plate girder bridge with non-integral abutments, corral rails, and an average skew of 24.4 degrees. LC-HPC-9 is 131.65 m (431.9 ft) long with three spans lengths of 40.0, 50.0, and 40.0 m (131.2, 164.0, and 131.2 ft), and is 12.80 m (42.0 ft) wide.

The top mat of reinforcing steel in the deck of LC-HPC-9 consists of No. 16 (No. 5) bars spaced at 180 mm (7.1 in.). The deck is monolithic and has 75 mm (3.0 in.) of top cover, 35 mm (1.4 in.) of bottom cover, and a total depth of 220 mm (8.7 in.).

Concrete. O'Brien Ready-Mix provided the concrete for LC-HPC-9 from a mobile ready-mix plant located 2.4 km (1.5 mi) south of Pleasanton, Kansas, approximately 9.6 km (6 mi) from LC-HPC-9. The average haul time was 38 minutes for the qualification slab and 34 minutes for the deck. The specifications for LC-HPC-9 required a maximum cement content of 317 kg/m^3 (535 lb/yd^3) and a *w/c* ratio of 0.42, for a total paste volume of 23.3%. As with the other LC-HPC bridges in this contract (LC-HPC-8 and 10), the paste content of this mixture was increased to aid workability. The cement content for the mixtures placed were either 317 kg/m^3 (535 lb/yd^3) or 320 kg/m^3 (540 lb/yd^3), and the *w/c* ratios were increased to 0.44. The design air content was 8.0%.

The mixture contained four aggregates, including two granite coarse aggregates (BSG_{SSD} = 2.63) from Arkansas and two natural sand fine aggregates (BSG_{SSD} = 2.63). The granite coarse aggregate with the largest MSA was not used in the corral rail concrete mixture.

Qualification Batch (3/25/2009). At the contractor's request, the first truckload of concrete at the second placement attempt for the qualification slab on March 25, 2009 served as the qualification batch for LC-HPC-9. KDOT and KU personnel were on site, with the qualification slab located just to the south of the LC-HPC-9 bridge. The concrete contained 320 kg/m^3 (540 lb/yd^3) of cement and had a *w/c* ratio of 0.44. Upon delivery to the qualification slab site, the concrete was tested from the truck. The air content was 9.2%, the slump was 90 mm (3.5 in.), and the concrete temperature was 16°C (60°F).

Qualification Slab – attempt 1 (3/23/2009). A pre-construction teleconference meeting occurred on March 12, 2009 for LC-HPC-9 during which several specification items were discussed including the new requirements for air temperature both during placement and the curing period, time requirements for the burlap placement, and the recommendation to use hand-held fogging equipment instead of the machine mounted fogging equipment. The contractor elected to follow the new specifications for air temperatures.

The first attempt at constructing the qualification slab was made on March 23, 2009 with concrete arriving on site at approximately 11:00 a.m. The qualification slab was located on the south side of the LC-HPC-9 bridge. The concrete for this placement contained 320 kg/m^3 (539 lb/yd^3) of cement and had a *w/c* ratio of 0.43. The concrete in the first (and only) truck was tested from the truck. The slump was 45 mm (1.75 in.), the air content was 7.4%, and the concrete temperature was 26°C (78°F). The concrete did not meet the specifications for temperature but appeared to be workable. Placement by pumping was attempted and the concrete pump became clogged and could not pump the concrete. The concrete was retested at 11:08 a.m. by a different crew. For the second set of test results, the slump was 40 mm (1.5 in.), and the air content was 6.8%. The placement was cancelled and no concrete was placed in the qualification slab. No concrete was placed in the qualification slab on March 23, 2009.

It was believed that the slump was too low for the concrete to pump, even though the concrete appeared (by sight) to be workable. It was decided to try again on another day with a higher slump. Recorded air temperatures during the first attempt to place the qualification slab were 22° and 21°C (72° and 69°F).

Qualification Slab – attempt 2 (3/25/2009). The second attempt at constructing the qualification slab was made on March 25, 2009 with concrete arriving on site at approximately 1:55 p.m. To increase the workability for this placement, the cement content for the concrete was increased to 320 kg/m^3 (539 lb/yd^3) of cement. The *w/c* ratio remained at 0.44. At the contractor's request, the first (and only) truckload of concrete on this day served as the qualification batch for LC-HPC-9, as discussed previously. The concrete in the first (and only) truck was tested from the truck. The slump was 90 mm (3.5 in.), the air content was 9.2%, and the concrete temperature was 16°C (60°F). The concrete met all of the specifications and appeared to be very workable. Placement by pumping with the same pump as used on the first attempt (3/23/2009) was attempted. At approximately 2:20 p.m. the pump was primed with mortar prior to pumping the concrete. When attempting to pump the concrete, the concrete pump again could not pump the concrete, the placement was cancelled, and no concrete was placed in the qualification slab on March 25, 2009.

The largest pieces of aggregate found in the concrete were close to 38 mm (1.5 in.) diameter. The concrete mix design was rechecked and compared with the mix designs used on previous bridges. The mix design appeared, on paper, to have a better gradation than the comparison bridges. The pump hose diameter was 115 mm (4.5 in).

It was believed that for this particular aggregate, the diameter of the individual particles retained on the largest sieve size [25-mm (1-in.)] was nearly the size of the next largest sieve [38 mm (1.5 in.)]. Many of the large aggregate particles were also elongated. Therefore some dimensions were even larger than 38 mm (1.5 in.), possibly even up to 50 mm (2 in.). Because they were elongated and could fit between the openings on the 38-mm (1.5-in.) sieve, these particles still met the requirements of being retained on the 25-mm (1-in.) sieve. It was concluded that because this mix contained more of the elongated and larger particles, it was clogging the pump. A general rule of thumb is to use a pump with hose diameter larger than three times the largest particle dimension. In this case, three times the largest particle dimension, approximately 50 mm (2 in.), would require a pump diameter of 150 mm (6 in.).

Theoretically, the solution was to choose a bigger pump diameter or change the concrete gradation. A larger pump diameter was not feasible, and since the concrete met specifications, the supplier was not required to change the mixture. KU attempted to arrange a trial batching and pumping day to develop a pumpable mixture. KU was prepared to increase the paste content and the *w/c* ratio to achieve a pumpable mixture. The contractor, however, elected to not attempt pumping again and chose to use conveyor belts for the deck placement.

Qualification Slab – attempt 3 (4/1/2009). The third attempt at constructing the qualification slab was successful on April 1, 2009 using a 39.6 m (130 ft) conveyor belt. Concrete arrived on site at approximately 10:50 a.m. The concrete had a cement content of 320 kg/m^3 (539 lb/yd^3) of cement and a *w/c* ratio of 0.44. The concrete in the first truck was tested before and after the conveyor belt. The test results from the truck indicated that the slump was 100 mm (4.0 in.), the air content was 9.7%, and the concrete temperature was 13°C (55°F). After the conveyor belt, concrete test results indicated that the slump was 75 mm (3.0 in.), the air content was 7.6%, and the concrete temperature was 14°C (58°F). The concrete from the first truck met all of the specifications. The drop from the conveyor to the deck was approximately 4.6 m (15 ft) resulting in a loss in air content of 2.1% and a loss in slump of 25 mm (1 in.). The second truckload of concrete did not meet specifications, and was high on air (9.9%) and slump [115 mm (4.75 in.)] after the conveyor best. Specimens made from the second truckload (with high air content) indicated 28-day compressive strengths of 23.1 MPa (3350 psi). The third truckload met specifications for air content (9.0%). The slump was not tested but appeared to be high.

Placement and finishing went smoothly, in part because the concrete had a high slump. Finishing was completed with a double-drum roller screed with one roller removed followed by a double pan drag. The burlap placement seemed generally slow with an average time of placement of 11 minutes, a minimum time of 6 minutes and a maximum time of 17 minutes. The crew moved the work bridges back and forth many times to place the layers of burlap separately.

After the qualification slab was completed, an impromptu meeting was held to discuss the upcoming deck construction. Options for placing the entire deck in one day rather than two separate placements were discussed. There was concern for public safety if placement were done from the companion bridge (Control 9) and for the rate of concrete delivery with the traffic control.

Deck placement (4/15/2009). The placement of LC-HPC-9 occurred on April 15, 2009, with construction starting at approximately 9:30 a.m. The last burlap was placed at 6:20 p.m., for a total time of 8.8 hours. The average placement rate for the placement was approximately 42 m^3/hr (55 yd^3/hr). Air temperatures during the placement ranged from 15 to 24ºC (59 to 76ºF). Given the options, the contractor chose to adopt the new specifications regarding the air temperature at the time of placement, and therefore waited to begin construction until the air temperature was above 10ºC (50ºF) because the high air temperature for the day was forecasted to exceed 16ºC (60ºF).

The concrete had a cement content of 320 kg/m^3 (539 lb/yd^3) of cement and a *w/c* ratio of 0.44. Concrete test records indicate that the slump ranged from 55 to 135 mm (2.25 to 5.25 in.) with an average of 86 mm (3.4 in.). Air contents ranged from 5.7% to 7.6%, with an average of 6.7%. The concrete temperature ranged from 16 to 21ºC (60 to 69ºF) with an average of 18ºC (64ºF). The first four trucks were adjusted at the site, adding back the water that had been withheld at the plant. Air-entraining agent was added to the first truck to increase the air content to meet specifications. The air-entraining agent dosage was increased throughout the day to adjust for low measured air contents. Four tested truckloads placed in the deck had air contents below 6.5%, with air contents of 5.9%, 5.7%, 6.1%, and 6.1%. Two tested truckloads placed in the deck had slumps above 100 mm (4 in.), with slumps of 135 mm (5.25 in.) and 105 mm (4.25 in.). All concrete placed in the deck met the temperature requirements. The loss of air and slump through the conveyor belt was not determined for this placement. Two fully equipped concrete testing stations were located at the truck delivery point and at locations for sampling from the deck. There were no delays in concrete delivery until the final backordered truck, which caused a delay of 25 minutes at the end of the deck. The average 30-day compressive strength for the LC-HPC-9 deck is 28.9 MPa (4190 psi).

The placement of LC-HPC-9 went smoothly. Placement was from north to south. The concrete was placed using two conveyor belts. The first conveyor belt was initially located at the north end of the deck and placed concrete over the finishing equipment for the first portion of the deck. The concrete drop from the conveyor to the deck was approximately 6.1 m (20 ft) determined by scaling from photographs from the first portion of the deck. The placement of the first portion of the deck is shown in Fig. 5.21(a). The second conveyor belt was positioned on the adjacent companion (southbound) bridge and placed the concrete while reaching over the river. The concrete drop from the conveyor to the deck is estimated to be 11 m (36 ft) by scaling from multiple photographs through the center portion of the placement. The placement of center portion of the deck is shown in Fig. 5.21(b). During the placement of the center portion of the deck, the first conveyor was moved from the north side of the bridge to the south side of the bridge. The final (south) portion of the bridge was placed with the conveyor belt positioned on the south side of the bridge, with concrete placed in front of the finishing equipment. The conveyor did not reach over the finishing equipment for the final portion of the placement. The concrete drop from the conveyor to the deck for the south portion of the deck was 3 to 4.6 m (12 to 15 ft), as determined by scaling from photographs. The placement of the south (last) portion of the deck is shown in Fig. 5.21(c). The conveyor belt truck was repositioned once for each of the three placement sections (north, center, and south) causing a slight delay in concrete delivery for each repositioning.

Fig. 5.21 (a) For the north portion of deck the drop was approximately 6.1 m (20 ft)

Fig. 5.21 (b) For the center portion of deck the drop was approximately 11 m (36 ft)

(c) For the south portion of deck the drop was approximately 4.6 m (15 ft)

Fig. 5.21 The concrete drop from conveyor belt to deck varied for the three portions of the deck placement.

For much of the deck, concrete was placed approximately 3 to 4.6 m (10 to 15 ft) in front of the finishing equipment, often at an angle corresponding to the skew of the bridge as shown in Fig. 5.22.

Fig. 5.22 Concrete placed in front of the finishing equipment at a skew

Consolidation was achieved with a mechanically controlled gang vibrator system consisting of 11 mounted hand vibrators (capacity up to 12 vibrators), mounted on the finishing bridge. The system, shown in Fig. 5.23, was easily assembled and disassembled.

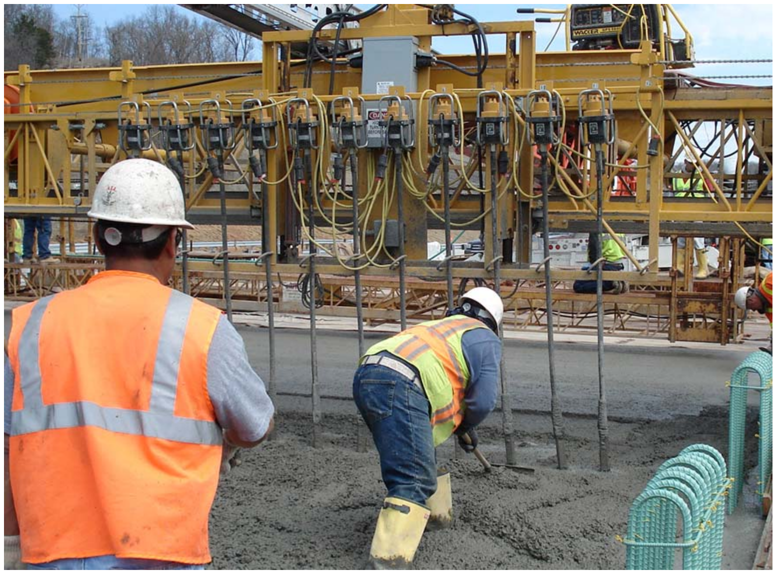


Fig. 5. 23 Gang vibrator system used for consolidation.

The concrete was finished using a double-drum roller screed with one roller removed and a double pan drag attached to the screed. Floating was performed only at the beginning and the ends of the deck at locations where the double pan drag could not reach. Fogging was not used, and the evaporation rate was below 1.0 kg/m^2/hr (0.2 lb/ft^2/hr) all day.

Rolls of presoaked burlap were pre-positioned along the deck and unrolled across a work bridge following the finishing bridge. When the burlap was unrolled, dry spots were found because it had been rolled too tightly to become fully saturated. Workers tried to place the dry burlap and rewet it once it was placed on the deck. This was stopped quickly, and they were told to rewet it before placing it on the deck. Workers had to be reminded of this several times during the first third of the deck and once for the very last concrete placed. Workers sprayed the rolls of burlap, but this was only somewhat successful and the burlap still contained large dry spots when it was unrolled, as shown in Fig. 5.24.

Fig. 5.24 Drying burlap that needed to be rewet

The burlap placement was generally placed at a reasonable rate, with some periods during which placement fell behind. With prompting by the supervisors, the workers caught up to the finishing equipment. The average time between finishing and burlap placement was 10 minutes, with a minimum time of 3 minutes and a maximum time of 18 minutes. Seventeen of 43 (40%) locations timed exceeded the 10 minute requirement, with times ranging from 11 to 18 minutes. The two layers of burlap were placed separately, with the edges overlapping. The in-place burlap was rewet with spray hoses during the placement and ponding occurred on the concrete surface at the east (lower) side of the deck. Holes were drilled in the forms to allow the ponded water to flow out. After inspection, the northeast corner of deck received a 3rd layer of burlap because it was drying out faster than the other portions of the deck. The contractor was reminded that the polyethylene sheeting needed to be placed within 12 hours.

While placing concrete in the center portion of the deck from the companion bridge, traffic control was required, and only a single lane with a chase car and traffic control was allowed. The maximum load for the companion bridge included the conveyor truck, two fully loaded concrete trucks and a single (west) lane fully loaded.

At the south end of the deck, concrete had to be backordered causing a delay. The southeast corner of the deck remained unfilled. During the delay, the deck was finished as far as possible, the finishing equipment was moved off of the deck, and all of the concrete (finished and unfinished) was covered with wet burlap to prevent drying.

The girder surface temperatures were monitored throughout the day using an infrared thermometer. In general, placing concrete on the deck had a significant influence on the girder temperature.

For locations that concrete had not yet been placed, the girder temperatures were approximately the same as or close to the air temperature until 1:30 p.m. From 1:30 p.m. until the end of the construction, the temperature of the top girder flanges exceeded the air temperatures due to heating from the sun. Temperatures throughout the depth of the girders were also measured. For girders in the portion of the deck that concrete had not yet been placed, the average temperature differential between the top flange of the girder and the center of the girder web was 13°C (24°F), and the average temperature differential between the top and bottom flanges was 19°C (34°F). For girder locations where concrete had been placed, the temperature differentials were very different. For the east girder, at a location that was in contact with the concrete (north end of the deck), the temperature differential between the top flange and the center of the web was only 0.6°C (1°F) and between the top and bottom flanges was 2°C (4°F), and the girder temperature [18°C (64°F) at the top flange and 16°C (60°F) at the bottom flange] was very close to the concrete temperature [average 18°C (64°F)]. For the same girder, at a location that was not in contact with the concrete (south end of the deck), the temperature differential between the top flange and the center of the web was 9°C (17°F) and between the top and bottom flanges was 16°C (28°F), with girder temperatures ranging from 29°C (84°F) at the top flange to 13°C (56°F) at the bottom flange.

The initial 14-day curing period was completed on April 29, 2009. No additional curing was required because the air temperature never dropped below 4°C (40°F) during the curing period.

The deck forms were removed between May 12 and May 27, 2009, 27 to 42 days after the deck placement.

Personnel Response and Post-Construction Conference. A post-construction conference was held on June 3, 2009 with representatives from KDOT, the contractor, and KU present. The contractor indicated that the construction process went smoothly but required additional labor due to laying two layers of burlap, presoaking the burlap and because the concrete could not be pumped. Bids would have to be higher for future projects because of the extra labor.

During the discussion about concrete pumpability, KDOT representatives indicated that the pump was too small for the concrete, and the contractor stated that the ready mix supplier had specifically required that the contract state that the supplier was not responsible for the pumpability of the mix.

KDOT representatives were concerned that with the new cold weather specifications more precautions should be taken to protect young concrete from freezing during the first few days after placement.

The frequency of testing was discussed, and it was determined that the rate of placement required in the new Phase 2 specifications was approximately the same as the standard KDOT testing rate for the area except for one additional slump and temperature test for every six truckloads.

The inspector for KDOT indicated that the drop at the end of the conveyor was too high and the burlap was not wet enough before placement. He liked using standard practices for curing the rail.

The burlap was not always fully saturated before attempting placement on the deck. Workers may not place unsaturated burlap on the deck. Soaker hoses were placed at the high point of the deck superelevation, and water subsequentially flowed across the entire placement. Drilling holes in the forms worked well to allow water to drain off the deck without ponding.

Backordered concrete at the end of the placement caused a delay of 30 minutes at the end of the placement.

Lessons Learned. A good inspector significantly helps the quality control for construction.

Public safety is of primary importance. One traffic accident (fatality) that occurred the previous year (2008) shut down the job site and delayed construction.

Girder temperatures are not uniform at the locations where concrete has not been placed and are not necessarily equivalent to the ambient air temperature. The girder in contact with concrete had a considerably more uniform temperature through its depth than the portion of the girder not in contact with the concrete.

The rate of testing specified in the new Phase 2 specifications is approximately the same as the KDOT standard rate of testing.

The new Phase 2 specifications should be adjusted to provide longer protection from freezing for young concrete than just the first 24 hours after placement.

Placing concrete with a conveyor can be very efficient, but the elevation of the drop should be limited.

5.3.10 Control Bridge 9

Control 9 is the southbound bridge on US-69 over the Marais Des Cygnes River, 4 miles north of Pleasanton, KS on US-69. LC-HPC-9 is the northbound companion bridge at the same location. Control 9 and LC-HPC-9 were let in the same contract as bridges LC-HPC-8, 10, and Control 8/10. The contract was awarded to Koss Construction, and Control 9 and LC-HPC-9 were subcontracted to United Construction.

Dates related to the construction of Control 9 are shown in Table 5.10. Control 9 was constructed in a single phase with construction spanning over seven months in 2007 and 2008, with a completion date of May 29, 2008.

Table 5.10 – Construction Dates for Control 9

Item Constructed	Date Completed
Subdeck placement	11/3/2007
SFO placement 1 (east)	5/21/2008
SFO placement 2 (west)	5/29/2008

Design. The southbound US-69 over the Marais Des Cygnes River Bridge is a three-span, steel plate girder bridge with non-integral abutments, corral rails, and an average skew of 23.9 degrees. Control 9 is 131.65 m (431.9 ft) long with three spans lengths of 40.0, 50.0, and 40.0 m (131.2, 164.0, and 131.2 ft), and is 12.80 m (42.0 ft) wide.

The top mat of reinforcing steel in the deck of Control 9 consists of No. 16 (No. 5) bars spaced at 180 mm (7.1 in.). The deck has 75 mm (3.0 in.) of top cover and 30 mm (1.2 in.) of bottom cover. The subdeck depth is 180 mm (7.1 in.), and the SFO depth is 40 mm (1.6 in.), for a total depth of 220 mm (8.7 in.).

Concrete. The concrete mix designs for both the subdeck and the SFO meet the KDOT specifications for this type of structure. The concrete mix for the subdeck contained 363 kg/m^3 (611 lb/yd^3) of Type I/II cement, a *w/c* ratio of 0.40 and 6.5% entrained air. The aggregate used in the subdeck was a 50:50 blend of natural sand (BSG_{SSD} = 2.62) and limestone (BSG_{SSD} = 2.60). The silica fume overlay concrete included a 7% silica fume replacement of cement, or 26 kg/m^3 (44 lb/yd^3), 350 kg/m^3 (589 lb/yd^3) of Type I/II cement, a *w/cm* ratio of 0.37, and an air content of 6.5%. Quartzite (BSG_{SSD} = 2.63) from South Dakota was used as the coarse aggregate.

Deck Placement. The deck placements were not observed and standard practices are assumed to have been used, including a 7-day curing period.

Construction occurred in three placements. The subdeck was constructed on November 3, 2007. The east SFO was placed next on May 21, 2008, almost 7 months later, and the west SFO was placed on May 29, 2008.

Test records for the subdeck (11/3/2007) indicate that the average slump was 67 mm (2.6 in.) with a minimum of 50 mm (2 in.) and a maximum of 95 mm (3.75 in.). The average air content was 6.2% with a minimum of 5.4% and a maximum of 7.1%. Placement took approximately 7 hours. The average haul time, or time from loading to truck discharge, was 36 minutes, with a minimum haul time of 20 minutes and a maximum haul time of 65 minutes.

Test records for the first (east) placement of the SFO (5/21/2008) indicate that the average slump was 193 mm (7.6 in.) with a minimum of 170 mm (6.7 in.) and a maximum of 215 mm (8.5 in.). The average air content was 6.2% with a minimum of 5.7% and a maximum of 6.7%. The placement took approximately 3.5 hours. The average haul time, or time from loading to truck discharge, was 41 minutes, with a minimum haul time of 25 minutes and a maximum haul time of 50 minutes.

Test records for the second (west) placement of the SFO (5/29/2008) indicate that the average slump was 90 mm (3.5 in.) with a minimum of 70 mm (2.75 in.) and a maximum of 110 mm (4.3 in.). The average air content was 5.6% with a minimum of 5.2% and a maximum of 5.9%. The placement took approximately 4 hours. The average haul time was 49 minutes, with a minimum haul time of 30 minutes and a maximum haul time of 70 minutes.

The environmental conditions and evaporation rates from construction diaries for the placements were not obtained. Weather station data from the Garnett Airport indicate that the daily high/low air temperatures for the three placements were 20º / –1ºC (68º / 30ºF) on November 3, 2007, 23º / 7ºC (73º / 45ºF) on May 21, 2008, and 21º / 13ºC (70º / 55ºF) on May 29, 2008. For the subdeck, the air temperature dropped below 4ºC (40ºF) on days 1, 2, 4, 5, 6, and 7 of the 7-day curing period. For the SFO placements, the air temperature never dropped below 4ºC (40ºF) during the 7-day curing period.

The deck forms were removed from April 4 to April 22, 2008, 151 to 169 days after the subdeck was placed.

5.3.11 LC-HPC Bridge 11

The eleventh LC-HPC bridge deck let (LC-HPC-11) is the eastbound bridge located on US-50 over the K&O railroad tracks in Hutchinson, KS. The contract contained other bridges not included in this study and was awarded to Koss Construction. The westbound bridge at the same location was not used as a control bridge for this study because it was a haunched slab and does not match the type of structures used in this study. It was subcontracted to King Construction. LC-HPC-11 was the fifth LC-HPC bridge constructed in Kansas and was completed on June 9, 2007. Dates related to the construction of LC-HPC-11 are shown in Table 5.11.

Table 5.11 – Construction Dates for LC-HPC-11

Item Constructed	Date Completed
Qualification Batch – attempt 1	5/22/2007
Qualification Batch – attempt 2	5/23/2007
Qualification Slab	5/25/2007
Qualification Batch - attempt 3	6/6/2007
Qualification Batch - attempt 4	6/7/2007
LC-HPC Deck	6/9/2007
Post-Construction Meeting	9/28/2007

Design. The US-50 over the K&O Railroad bridge, sometimes referred to as the Hutchinson bridge or the Reno County bridge, is a three-span, composite (rolled) steel girder bridge with integral abutments, jersey barriers, and no skew.

LC-HPC-11 is 35.9 m (117.78 ft) long. The three span lengths for LC-HPC-11 are 10.95 m (35.9 ft), 14.0 m (45.9 m) and 10.95 m (35.9 ft). The total width of the Hutchinson bridge is 12.95 m (42.5 ft), and the deck was constructed in one placement. The LC-HPC-12 deck is monolithic with a total depth of 220 mm (8.7 in.), 75 mm (3 in.) of top cover, and 30 mm (1.2 in.) of bottom cover. The top mat of reinforcing steel consists of No. 16 (No. 5) bars spaced at 175 mm (6.9 in.).

Concrete. Mid-America Redi-Mix provided the concrete for the LC-HPC-11 deck, with a haul distance of 6 km (3.7 mi) and a haul time of approximately 8 minutes.

The concrete for LC-HPC-11 contained 317 kg/m^3 (535 lb/yd^3) of Type I/II cement and had a *w/c* ratio of 0.42. The design air content was 8.0%. The mixture required four aggregates to meet the combined aggregate gradation specification, and included three granite coarse aggregates (BSG_{SSD} = 2.78) from Oklahoma, and one natural fine aggregate (BSG_{SSD} = 2.61).

Qualification Batch – attempts 1 and 2 (5/22/2007 and 5/23/2007). A 3.1 m^3 (4 yd^3) trial batch was produced on May 22, 2007, but did not meet the specifications. The concrete had an air content of 6.3%, a slump of 215 mm (8.5 in.), and a concrete temperature of 18.9°C (66°F). Ice was used as a partial replacement for water at a rate of 38 kg/m^3 (64 lb/yd^3). The concrete temperature was tested after pumping, but it is not clear whether the slump and air were tested after pumping. It is not clear whether a simulated haul time was observed for this trial batch. Air temperatures in Hutchinson on May 22, 2007 ranged from 16° to 25°C (61° to 77°F).

The next day, on May 23, 2007, the qualification batch was produced but still did not meet specifications. The concrete had an air content of 7.9%, a slump of 80 mm (3.1 in.), but the concrete temperature was 25°C (77°F), exceeding the maximum allowable. No ice was used for this qualification batch. It is not clear whether the concrete was tested after pumping, nor whether a simulated haul time was observed for this trial batch. The placement of the qualification slab was allowed to proceed despite two unsuccessful batch attempts. Air temperatures in Hutchinson on May 23, 2007 ranged from 17° to 27°C (62° to 80°F).

KU personnel were not on site for the qualification batches.

Qualification Slab (5/25/2007). The qualification slab was placed on May 25, 2007, with placement beginning at approximately 10:45 a.m. The placement was completed in approximately 4 hours. The air temperatures during placement ranged from 22° to 23° C (71° to 74°F) and for the day from 10° to 20° C (50° to 68°F).

Concrete delivery and properties were the biggest challenge for the qualification slab. The first truckload of concrete did not meet the specifications for slump [190 mm (7.5 in.)] or air (11%), so the truck was rejected. The second truck had an air content of 9% before the pump, but after adding half of the water held back and remixing, the air content was 4.5% after the pump. After adding the water back, the concrete was not retested prior to the pump, so it is impossible to determine how much air loss occurred through the pump.

Trucks 3, 4, and 5 were tested from the slab, after the pump, but the sixth (and final) truck was tested before and after the pump. The air loss through the pump was 1% for truck 6. The average slump of the concrete placed in the qualification slab was 93 mm (3.7 in.). Two of the five truckloads placed in the slab had slumps of 120 mm (4.7 in.) and 155 mm (6.1 in.), exceeding the maximum allowable. The average air content was 6.7% with a minimum of 4.5% (truck 2 discussed previously) and a maximum of 9.0%. Four of the five truckloads placed in the slab had air contents (4.5%, 6.0%, 5.2%, and 5.0%) below the minimum allowable. The concrete temperature ranged from 17º to 20ºC (62º to 68ºF) with an average of 19ºC (66ºF). Overall, the concrete properties were inconsistent and there were long delays between truckloads (56, 12, 12, 23, 30 minutes).

Concrete was placed in the 12.95-m (42.5-ft) wide qualification slab with a pump. The pump became clogged with the concrete from truck 4. The pump operator pulled pieces of aggregate from the concrete that were elongated and approximately 75 mm (3 in.) long. The pump operator added a “half S-Hook” to the pump discharge at concrete truck 3.

The concrete was consolidated using two sets of gang vibrators consisting of four vibrators mounted on the finishing bridge and were manually operated to consolidate the concrete.

Finishing operations went smoothly. Finishing was completed with a single-drum roller screed followed by extensive bullfloating. The contractor was reminded to not overwork the surface, especially with fogging turned on. Rail reinforcement was not simulated in the qualification slab.

The fogging for the qualification slab worked very well. The equipment consisted of solid piping and 10 nozzles pointed up. It produced a large volume of fine fog and did not drip (Fig. 5.25). The fogging equipment was left on for the concrete delivery delays and did not accumulate water on the surface of the concrete. Hand held fogging equipment was available but not used for the qualification slab. During the long delays, the roller screed remained on and continued to work the concrete surface at a single location. The screed should be idled during delays.

Fig. 5.25 Fogging equipment that worked well, producing fog and did not drip

Behind the finishing bridge, burlap was placed between two work bridges, which were connected by wood framing with a separatation between the bridges. When unfolding the burlap, the workers utilized areas of the ground that were farther from the slab than would be realistic for the bridge placement, as shown in Fig. 5.26. Simulated walkways would have restricted movement to very close proximity to the deck (slab), and therefore a different technique for opening the burlap was necessary for the deck.

Fig. 5.26 Workers standing far from the slab does not accurately simulate conditions on the deck

Because of the delays in concrete delivery, burlap placement rates were very slow, but improved as placement proceeded. The average burlap placement time was 32 minutes, with placement times of 40, 49, 35, 20 and 14 minutes.

A conference call was held on May 29, 2007 to discuss the qualification slab and the upcoming deck placement. A new mix design was required containing less of the coarsest aggregate to minimize the risk of clogging the pump with the large (3 in.) aggregate particles. A new qualification batch was therefore needed. It was emphasized that concrete must meet specifications and that delivery without delays was important. Concerns with the construction procedures that were noted during the qualification slab, such as the finishing and burlap handling, were discussed in preparation for the deck. Due to the large aggregate particles and favorable access to the bridge, the decision was made to use a conveyor belt for the bridge deck instead of a pump.

Qualification Batch – attempts 3 and 4 (6/6/2007 and 6/7/2007). A trial batch (the 3rd attempt) was produced on June 6, 2007, but did not meet the specifications. The concrete had high air content, slump, and temperature. The results were not reported. Air temperatures in Hutchinson on June 6, 2007 ranged from 17° to 28°C (62° to 83°F).

The next day, on June 7, 2007, the qualification batch was produced (the 4th attempt). Tests were run immediately after batching and then again after an additional 5 L/m^3 (1 gallon/yd^3) of water was added to the load. Initial testing indicated that the concrete had an air content of 7.1%, a slump of 72 mm (2.8 in.), and a temperature of 21°C (70°F). Ice was used for temperature control at a rate of 48 kg/m^3 (80 lb/yd^3). It is not clear whether a simulated haul time was observed for the batching. After adding the water and remixing, testing indicated that the concrete had an air content of 7.8%, a slump of 80 mm (3.1 in.), and a temperature of 22°C (71°F). Air temperatures in Hutchinson on June 7, 2007 ranged from 22° to 31°C (71° to 87°F). It is not clear why nor how much water was withheld, nor what the final mixture proportions (water content, *w/c* ratio) were.

KU personnel were not on site for the qualification batches.

Deck placement (6/9/2007). The placement of LC-HPC-11 occurred on June 9, 2007, with construction starting at approximately 5:50 a.m. The last burlap was placed at 11:20 a.m., for a total time of 5.5 hours. The average placement rate for the placement was approximately 19 m^3/hr (24 yd^3/hr). Air temperatures during the placement ranged from 14º to 22ºC (57º to 72ºF). Air temperatures for the day ranged from 9º to 23ºC (49º to 74ºF).

Most concrete testing was performed on samples taken from the truck, rather than at the point of placement. Concrete test records indicate that the slump ranged from 55 to 100 mm (2.25 to 4.0 in.) with an average of 79 mm (3.1 in.). Air contents from samples taken at the trucks ranged from 6.5% to 9.2%, with an average of 7.6%. The one truckload that did not meet specifications (the third truck) had an air content of 6.0% and was placed in the west abutment. Trucks 4 (rejected) and 5 (accepted) were subsequentially tested. As discussed previously, the concrete was placed with a conveyor belt. The conveyor was positioned with a 3.7 to 4.6 m (12 to 15 ft) drop. One air test near the end of construction indicated a loss in air content of 2.4% through the conveyor. To help minimize losses in air content, concrete should not be allowed to free-fall for more than 1.5 m (5 ft). The concrete temperature ranged from 15º to 18ºC (59º to 64ºF) with an average of 16ºC (61ºF). Ice was used to control the concrete temperature. The first five trucks were placed directly from the chute. There was one delay in the concrete delivery from 10:28 until 10:41 a.m. Large coarse aggregate particles, shown in Fig. 5.27, were again found in the concrete during placement. A grate with approximately 100-mm (4-in.) openings was placed over the loading hopper to the conveyor.

Fig. 5.27 A large coarse aggregate particle found in the concrete during the placement of LC-HPC-11

For LC-HPC-11, the average time from loading to discharge was 34 minutes, with a maximum time at the beginning of the placement of 34 minutes and a minimum time of 13 minutes.

The placement of LC-HPC-11 went smoothly. Placement was from west to east. The concrete was placed in the west (first) abutment and the first 10 ft of the deck directly from the truck chutes. The remainder of the bridge deck was placed using a conveyor belt. The first conveyor belt was located at the east end of the deck and placed concrete approximately 3 m (10 ft) in front of the finishing equipment without reaching over it. The concrete drop from the conveyor to the deck was approximately 3.7 m (12 ft).

Consolidation was performed by hand vibration for the first 3 m (10 ft) of the deck. The distance between insertion points was not estimated during the placement, but from photographs the distance was clearly larger than for the gang vibration systems (Fig. 5.28). The rest of the slab was consolidated using the same system described for the qualification slab.

Fig. 5.28 Insertion points for hand vibration at the west end of LC-HPC-11 are farther apart than for the gang vibration.

Finishing operations went smoothly. The concrete surface finished well with a single-drum roller screed and a pan drag. Bullfloating was not used for the deck until the last few feet on the east side. The pan drag occasionally produced small ridge lines approximately 1-2 mm high, which could have been avoided with a slight adjustment of the pan.

The fogging equipment was the same as for the qualification slab, as described previously. It worked well and produced a fine fog without dripping.

Workers carried the burlap to the deck throughout the placement, instead of delivering it to the deck with a crane. It was unfolded and hung over the formwork railing, left to drip off the side of the formwork to prevent dripping from occurring on the deck surface.

The burlap was unrolled on the side of the deck. It was carried onto two work bridges and placed on the deck in double layers. In the same way as for the qualification slab, the work bridges were connected and separated by wood formwork, keeping the distance between the bridges constant. The burlap placement was somewhat slow. Placement times ranged from 4 to 19 minutes, with an average of 14 minutes. The time to burlap placement met the 10-minute maximum at only 3 of 14 stations (21%) timed along the deck, with times of 10, 4, and 8 minutes. Additional personnel would have been helpful to deliver burlap to the deck, as would the use of a crane. Hand-held fogging equipment was used to keep the burlap wet after placement. The evaporation rate ranged from 0.10 to 0.34 kg/m^2/hr (0.02 to 0.07 lb/yd^2/hr) during the placement.

In the final stages of the placement, concrete was pre-placed in the abutment when the finishing equipment was still about 10 m (30 ft) from the end of the deck. Because of this, there was very little delay in finishing the end of the deck.

Ponded water was noticed on the south side of the deck at the barrier steel near the end of the deck placement. When this was noticed, the burlap rewetting was stopped.

Unique Considerations. The Hutchinson bridge (LC-HPC-11) is located approximately 3 hours from Lawrence. Because of the long travel time, KU personnel were not present for the qualification batch. This may have contributed to the difficulties with concrete production because the batching was not done properly by simulating haul time, requiring concrete temperature control, or adding all of the water to the truck at the beginning of the batch.

This was the first and only LC-HPC bridge deck cast with granite from Oklahoma. The granite for all the other LC-HPC bridge decks was a single supplier in Arkansas.

Personnel Response and Post-Construction Conference (9/28/2007). A post-construction conference was held on September 28, 2007. The overall impression from KDOT and the contractor was very positive. The contractor indicated that they drilled holes in the forms to allow the ponding water to drain. No cracks or honeycombing were found on the deck when the forms were removed. KDOT indicated that the rate of testing was more difficult to accommodate during the deck placement.

Lessons Learned. The air loss through a conveyor can be significant. It is important to test the concrete before and after the conveyor before placing any concrete in the deck, to determine the air loss through the conveyor. Ideally, concrete should be tested at the point of deposit on the deck to ensure the placed concrete meets specifications and will have the desired properties.

Gang vibration provides more thorough consolidation of the concrete than hand vibration. The insertion points for gang vibration systems are usually closer than spacing obtained with hand-held vibrators. For gang vibration, the vibrators are inserted and removed vertically as is consistent with good concrete practice.

5.3.12 Control Bridge 11

Control 11 is the bridge on US-50 over the BNSF railroad in Emporia, KS. Control 11 was the only bridge in the contract. The contract was awarded to A. M. Cohron & Son, Inc. The concrete for the deck was supplied by Builders Choice Concrete in Emporia, KS. Dates related to the construction of Control 11 are shown in Table 5.12. Control 11 was constructed in a single phase with a completion date of March 28, 2006.

Table 5.12 – Construction Dates for Control 11

Item Constructed	Date Completed
Subdeck placement 1 – North half	2/3/2006
Subdeck placement 2 – South half	2/14/2006
Silica Fume Overlay placement	3/28/2006

Design. The US-50 over the BNSF railroad bridge is a three-span, steel plate girder bridge with integral abutments, jersey barriers, and a skew of 24.3 degrees. Control 11 is 86.83 m (284.9 ft) long with three spans lengths of 25.4, 36.0, and 25.4 m (83.3, 105.0, and 83.3 ft), and is 20.35 m (66.8 ft) wide.

The top mat of reinforcing steel in the deck consists of No. 16 (No. 5) bars spaced at 180 mm (7.1 in.). The deck has 75 mm (3.0 in.) of top cover and 30 mm (1.2 in.) of bottom cover. The subdeck depth is 180 mm (7.1 in.) and the SFO depth is 40 mm (1.6 in.), for a total depth of 220 mm (8.7 in.).

Concrete. The concrete mix designs for both the subdeck and the SFO meet the KDOT specifications for this type of structure. The concrete mix for the subdeck contained 357 kg/m^3 (600 lb/yd^3) of Type I/II cement, a *w/c* ratio of 0.40, and an air content of 6.5%. The aggregate used in the subdecks was a 50:50 blend of natural sand (BSG_{SSD} = 2.56) and limestone (BSG_{SSD} = 2.63). The silica fume overlay concrete included a 7% silica fume replacement of cement, or 26 kg/m^3 (44 lb/yd^3), 346 kg/m^3 (581 lb/yd^3) of Type I/II cement, a *w/cm* ratio of 0.37, and an air content of 6.5%. Quartzite (BSG_{SSD} = 2.63) from South Dakota was used as the coarse aggregate.

Deck Placement. The deck placements were not observed, and standard practices are assumed to have been used, including a 7-day curing period.

Construction occurred in three placements. The north half of the subdeck was constructed on February 3, 2006. The south half of the subdeck was placed on

February 14, 2006. The final placement, the silica fume overlay, was constructed on March 28, 2006.

Test records for the placement of the north half of the subdeck (2/3/2006) indicate that the average slump was 90 mm (3.5 in.) with a minimum of 60 mm (2.25 in.) and a maximum of 120 mm (4.75 in.). The average air content was 7.2% with a minimum of 6.8% and a maximum of 7.5%. The placement took approximately 5 hours. The average haul time, or time from loading to truck discharge, was 29 minutes, with a minimum haul time of 23 minutes and a maximum haul time of 43 minutes.

Test records for the placement of the south half of the subdeck (2/14/2006) indicate that the average slump was 103 mm (4.1 in.) with a minimum of 65 mm (2.5 in.) and a maximum of 130 mm (5.25 in.). The average air content was 7.0% with a minimum of 6.0% and a maximum of 7.9%. The placement took approximately 3.5 hours. The average haul time was 23 minutes, with a minimum haul time of 17 minutes and a maximum haul time of 35 minutes. KDOT construction dairies indicate that this subdeck placement was covered with burlap and blankets after casting.

The two test records for the SFO (3/28/2006) indicate that the average slump was 78 mm (3.1 in.) with a minimum of 65 mm (2.5 in.) and a maximum of 90 mm (3.5 in.). The average air content was 6.0% with a minimum of 5.0% and a maximum of 7.0%. The placement took approximately 5 hours. The average haul time was 34 minutes, with a minimum haul time of 26 minutes and a maximum haul time of 43 minutes.

Weather station data from the Emporia Airport indicate that the daily high/low air temperatures for the three placements were 16º / –1ºC (61º / 30ºF) on February 3, 2006, 17º / –7ºC (62º / 20ºF) on February 14, 2006, and 11º / –1ºC (52º / 30ºF) on March 28, 2006. For both the first placement of the subdeck (north half) and the second placement of the subdeck (south half), the air temperature dropped below 4ºC (40ºF) on each of the days of the 7-day curing period. For the first subdeck placement (north half), construction diaries on the day of placement do not indicate any special protection from cold weather conditions. However, additional blankets were added on day 2 of the curing, and a heating system was put in place on day 3 of the curing. For the second placement of the subdeck (south half), the air temperature did not rise above –1ºC (30ºF) on four days of the 7-day curing period. Construction diaries indicate that on the day of placement the subdeck placement was covered with burlap and blankets, and a heating system was put in place the day after placement. For the SFO placements, the air temperature dropped below 4ºC (40ºF) on three of the days during the 7-day curing period. The construction diaries show no record of blankets or heating for the SFO.

Forms were removed from the first subdeck placement (north half) on days 12, 13 after placement, and possibly on day 17. Forms were removed from the second subdeck placement (south half) on day 13 after placement, but some removal may have occurred on day 6. Deck forms were also removed on Feburary 20, 2006, but construction diaries are not clear as to the location of the removal on this date. If it was for the first placement (north half), it occurred on day 17 after placement, if it was for the second placement (south half) it occurred on day 6 after placement.

5.3.13 LC-HPC Bridge 4

The third through the sixth LC-HPC bridge decks let in Kansas (LC-HPC-3, 4, 5, and 6) were let in a single contract, also including Control 3, 4, 5, and 6, which was awarded to Clarkson Construction. These eight bridges were a small portion of the whole contract, which was, at the time, the largest single contract awarded in Kansas. The contract included significant transportation infrastructure improvements to major highways, bridges (12 total), interchanges, and the south loop of I-435 in Johnson County, Kansas.

LC-HPC-4 was the sixth LC-HPC deck constructed in Kansas and the first of this contract to be constructed. It is the first unit of the bridge located on the southbound US-69 ramp over 103rd Street to the SB-69 ramp in Kansas City. Practically, when traveling south on US-69 connecting to I-435, LC-HPC-4 is the first portion of the bridges that are sometimes referred to as the flyovers at the US-69/I-435 interchange, before the US-69 interchange splits into the west and eastbound I-435 flyovers.

The contract included qualification batches and qualification slabs for each of the four LC-HPC decks included in the contract. At the contractor's request, three of the four qualification batches and decks were waived because the contractor had prior successful experience placing LC-HPC at five separate placements. The qualification batch and slab for LC-HPC-4 are therefore also those used for LC-HPC-3, 5, and 6.

As described in detail later, although not planned, LC-HPC-4 was constructed in two placements due to an electrical outage during the first placement. The bridge deck was completed on October 2, 2007. Dates related to the construction of LC-HPC-4 are shown in Table 5.13.

Table 5.13 – Construction Dates for LC-HPC-4

Item Constructed	Date Completed
Qualification Batch	6/7/2007
Qualification Slab	9/14/2007
LC-HPC Deck – Placement 1 (stopped at header)	9/29/2007
LC-HPC Deck – Placement 2 (completed)	10/2/2007
Post-Construction Meeting	5/28/2008

Design. LC-HPC-4, the first (north) unit of the southbound US-69 ramp bridge over the 103rd Street to I-435 ramp, is a four-span, steel plate-girder bridge with non-integral abutments, jersey barriers, and no skew. The second (south) unit is connected to Unit 1 (LC-HPC-4) with a finger joint. The geometry of Unit 2 is more complex than Unit 1 as it begins the split of southbound US-69 to two separate flyover structures. It is a 4-span, steel plate-girder bridge with one integral end condition at the north abutment and one non-integral end condition at Pier 4. It has jersey barriers, and the skew varies for each pier.

The whole bridge, LC-HPC-4 (Unit 1) and Unit 2 together, is 185.2 m (607.5 ft) long, with lengths for LC-HPC-4 (Unit 1) of 115.4 m (378.6 ft) and Unit 2 of 69.8 m (228.9 ft). The four span lengths for LC-HPC-4, from the north abutment to Pier #4 are 25.4 m (83.3 ft), 32.0 m (105.0 ft), 32.0 m (105.0 ft), and 25.93 m (85.1 ft).

The total width of LC-HPC-4 is 12.43 m (40.78 ft). Placement was from south to north. As mentioned previously, LC-HPC-4 was constructed in two placements, the first being approximately 33.5 m (109.8 ft) long and stopped at a header just north of Pier #4 and the second being 81.5 m (265.7 ft) long.

The LC-HPC-4 deck is monolithic with a total depth of 220 mm (8.7 in.), 75 mm (3 in.) of top cover, and 30 mm (1.2 in.) of bottom cover. The top mat of reinforcing steel consists of No. 16 (No. 5) bars spaced at 250 mm (9.8 in.).

Concrete. For LC-HCP-4 and the other bridges in this contract (LC-HPC-3, 5, and 6), the concrete was the most challenging aspect of the project. The difficulties associated with the concrete supply impacted all aspects of the project, including the construction. A brief overview of the concrete is presented here, but a full understanding of the events, challenges, and mistakes associated with the concrete supply for this contract and bridge LC-HPC-4 is vital to achieving a full understanding of the construction experiences and results. Therefore, a detailed study of LC-HPC-4 and the other bridges associated with this contract (LC-HPC-3, 5 and 6), which is presented in the companion report by Lindquist et al. (2008), is strongly advised.

Fordyce Concrete, located approximately 27 km (16.8 mi) from the project, provided the concrete for all the bridges in the contract, including LC-HPC-4. The haul time for LC-HPC-4 was approximately 50 minutes. For placement 1, the average time from loading to discharge was 49 minutes, with a maximum time of 67 minutes and a minimum time of 28 minutes. For placement 2, the trip tickets indicate that the haul time for every truckload was exactly 60 minutes, in itself a possible indication of the problems associated with this placement.

This contractor and supplier had previously successfully completed LC-HPC placements on five separate occasions, but the concrete for LC-HPC-4 and the other bridges in this contract (LC-HPC-3, 5, and 6) had four important differences. First, although the specifications for LC-HPC-4 require a maximum cement content of 320 kg/m^3 (540 lb/yd^3) and a *w/c* ratio of 0.45, the contractor elected to use concrete containing 317 kg/m^3 (535 lb/yd^3) and a *w/c* ratio of 0.42, which was in line with the current recommendations for LC-HPC at the time. This reduction in the cement content and *w/c* ratio represented a reduction in the overall design paste content from 24.6% to 23.4%. Second, to achieve an optimized gradation, the supplier added a fourth aggregate, a manufactured sand, to the mixture. Third, two separate mixtures were qualified for the project, and used in the qualification slab and in LC-HPC-4. Finally, for LC-HPC-4, as well as the other bridges in the project (LC-HPC-3, 5, and 6), the moisture content on the manufactured sand and possibly on the coarse aggregate may have been overestimated, potentially aggravating the difficulties observed with workability and pumpability and resulting in significantly lower than reported *w/c* ratios. Higher than expected values for the compressive strengths for the bridges in this contract seem to agree with this possibility.

The two mix designs, one designed by KU Mix and an alternate mixture designed by the concrete supplier, both contained 317 kg/m^3 (535 lb/yd^3) and had a *w/c* ratio of 0.42. The design air content was 8.0%. Both mixtures contained four aggregates, including two granite coarse aggregates (BSG_{SSD} = 2.61) from Arkansas, and one natural river sand fine aggregate (BSG_{SSD} = 2.61), and one crushed granite manufactured sand (BSG_{SSD} = 2.61), from Arkansas. The gradations were different for the two mix designs, with the "KU Mix" designed mixture containing 33.0% of the manufactured sand, and the "Alternate Mixture" containing 13.0%. According to the optimization procedures and the blends, the KU Mix designed mixture met all the gradation requirements, had a better-balanced gradation curve and plotted better on the Modified Coarseness Factor Chart. Because there was some concern that the manufactured sand could cause workability and pumping problems, both mixtures were trial batched and used on the qualification slab with similar and acceptable results and the KU Mix designed mixture was selected for use on the deck. Significant pumping problems during the first placement, due to a variety of reasons discussed later, resulted in a switch to the Alternate Mixture for the second placement. Pumping difficulties persisted for the second placement. In retrospect, many factors contributed to the problems associated with the concrete, and the combined effect resulted in significant pumping difficulties and delays during both placements.

Qualification Batch (6/7/2007). Two concrete mix designs were qualified on the same day for LC-HPC-3, 4, 5, and 6 (contract group 3).

Test results indicated the first qualified mix (the KU Mix) had an air content of 9.6%, slump of 100 mm (4.0 in.), and concrete temperature of 22ºC (71ºF) after a simulated haul time of 27 minutes. The air content did not meet specifications. The second qualified mix (the Alternate Mixture) had an air content of 9.5%, slump of 125 mm (5.0 in.), and concrete temperature of 22ºC (72ºF) after a simulated haul time of 30 minutes. The slump results for the second mix did not meet specifications. Ice and chilled water were used to control concrete temperatures.

Even though neither of the trial batches met specifications, both were accepted because the inspectors wanted to “limit the amount of concrete wasted.”

Qualification Slab (9/14/07). At the contractors request, a single qualification slab for LC-HPC-3, 4, 5, and 6 (contract group 3) was allowed instead of four separate qualification slabs because the contractor had already successfully completed five placements of LC-HPC concrete.

The qualification slab was completed on September 14, 2007, with placement beginning at approximately 7:00 a.m. The placement was completed in 2 hours. Records indicate that the air temperature near the end of the placement was 17°C (64°F), and ranging for the day from 11° to19° C (52° to 66°F).

Placement operations went smoothly with no significant issues. Concrete was placed in the qualification slab with a relatively small pump without a fixture on the discharge to limit air loss. Two truckloads of each of the qualified concrete mixtures were delivered and tested. The Alternate Mix was placed first and had air contents (before pumping) of 7.0% for both trucks. Air was actually gained through the pump at a rate of 1.0% for the Alternate Mix. The slump values were 72 and 53 mm (2.75 and 2.25 in.), and the concrete temperatures were 18.5º and 17ºC (65º and 63ºF).

The KU Mix was placed last and had air contents (before the pump) of 6.9% and 5.6%. Air was actually gained through the pump at a rate of 0.1% for the KU Mix. The slump values were 40 and 34 mm (1.75 and 1.25 in.), and the concrete temperatures were 17º and 16.5ºC (63º and 62ºF). The last truckload had a slump of 34 mm (1.25 in.), which is below the 40-mm (1.5-in) minimum, and was pumped with no difficulties.

The average slump for all the concrete placed in the qualification slab was 50 mm (2.0 in.). The average air content was 6.6% with a minimum of 5.6% and a maximum of 7.0%. The concrete temperature ranged from 16.5º to 18.5ºC (62º to 65ºF) with an average of 17.3ºC (63ºF).

Concrete placement and finishing was generally slow. The concrete was finished with a single-drum roller screed and a bullfloat. A pan drag was initially used, but removed after approximately 1.5 m (5 ft). At some points, the finishing did not achieve a smooth concrete surface, and various combinations of finishing was tried, including a Fresno and bullfloating. The Fresno appeared to be too light and did not appear to work better than the bullfloat. Eventually, the pan drag was removed and bullfloating alone was used to provide the final finish. At one point the worker using the bullfloat used a hand-held water sprayer to wet the surface of the deck to help him finish. This was stopped immediately, but highlights the importance of the qualification slab for workers to become familiar with the techniques allowed for LC-HPC.

Rail reinforcement was present in the qualification slab.

The fogging equipment was mounted on the back side of the finishing bridge. The system consisted of solid pipe connecting plastic spray nozzles and was prequalified the day before the placement by running it for 15 minutes and then turning it off for 5 minutes. The nozzles produced a fine spray, but when directed downward, they appeared to deposit water on the surface of the concrete. The pipe was free to rotate and was connected to the finishing bridge with wire. At the beginning of the placement, the spray nozzles were pointed downward and sprayed water on the concrete surface (Fig. 5.29). This was corrected and nozzles were pointed up. The fogging equipment was eventually turned off.

Behind the finishing bridge, two work bridges were used to place the wet burlap. The burlap was pre-positioned on the work bridges, and was partially dry when the placement began. Some of the burlap delivered to the work bridges during the placement dripped water on the surface of the deck, but the water was not worked into the concrete surface.

Fig. 5.29 Fogging equipment pointed down and spraying the concrete surface with water.

For the four locations timed along the slab, the placement times were 36, 32, 11, and 13 minutes. The average burlap placement time was 23 minutes. The burlap placement times did not meet the specifications at any point for the qualification slab.

Deck Placement 1 (9/29/2007). The LC-HPC-4 deck placement was originally planned as one placement scheduled on September 29, 2007. The placement was unexpectedly halted about one-third of the way through the placement due to an electrical outage at the concrete ready-mix plant. During the placement, significant challenges in concrete supply and pumping occurred. Because an understanding of the experiences with the concrete is vital to an understanding of the construction experiences, an overview of the concrete experiences is presented here. Details about the concrete experiences are provided in the companion report by Lindquist et al. (2008). The *w/c* ratio for this placement was 0.42.

Construction started at approximately 1:30 a.m. The electrical outage occurred at approximately 4:00 a.m., and the placement ended at approximately 5:45 a.m. Air temperatures during the placement ranged from 19º to 21ºC (66º to 69ºF), with a minimum and maximum for the day of 13º and 29ºC (56º and 84ºF).

The concrete supplier had difficulty consistently supplying concrete that met the specifications, and the contractor was not able to effectively pump the concrete. Just prior to the electrical outage, the decision was made to switch from the concrete designed by KU Mix to the Alternate Mixture, which contained less of the manufactured sand, which the concrete supplier considered the cause of the pumping difficulties. In addition to the manufactured sand, several other important factors contributed to the difficulties experienced during the placement, including the pump used, and over-estimating the moisture content of the aggregates. During the placement of the qualification slab, a smaller pump operating at a higher pressure was used to place the concrete in the slab, which was at ground level. The KU Mix pumped adequately, even at slumps lower than allowed [35 mm (1.25 in.)]. For the bridge placement, a different and much larger pump was used to reach the elevated deck and the mixture pumped poorly. The new equipment should have been tested and approved prior to placement of the deck.

The concrete supplier had difficulty consistently supplying concrete that met the specifications. The average slump for all the concrete placed in the deck during placement 1 was 47 mm (2.1 in.), with a minimum of 18 mm (0.7 in.) and a maximum of 103 mm (4.1 in.). Five of the seven truckloads tested for slump and placed in the deck before the electrical outage had slumps lower than the minimum allowable slump [38 mm (1.5 in.)], and four of these had slumps less than the low-slump truckload [35 mm (1.25 in.)] that was pumped during the qualification batch. For the concrete placed before the electrical outage, the average slump was 33 mm (1.3 in.), lower than the required minimum 35 mm (1.5 in.). After testing, high-range water reducer was added directly to the trucks prior to discharge to the pump in an attempt to bring the slump up to about 75 or 100 mm (3 or 4 in.). Only one truckload was retested after the addition of the water reducer [slump = 56 mm (2.2 in.)]. Clearly, some of the difficulties in pumping resulted from the low slump. After the electrical outage, the last three truckloads were all accepted to reach the header. Of these three truckloads, one of them had a slump of 103 mm (4.1 in.) and one was not tested for slump.

The average air content for all the concrete placed in the deck during placement 1 was 8.5% with a minimum of 6.8% and a maximum of 11.6%. Before the electrical outage two truckloads were rejected for high air content (10.4% and 11.4%). Of the four truckloads tested for air content and placed in the deck before the electrical outage, the average air content was 7.2% with a minimum of 6.8% and a maximum of 7.8%. Of the three truckloads accepted after the electrical outage to reach the header, two of them had air contents (11.6% and 10.6%) exceeding the maximum allowable air content of 9.5%.

For this placement, chilled water and ice was used to control the concrete temperature, but the concrete temperature was not measured during placement. The average haul time from loading to discharge was 49 minutes, with an minimum time of 28 minutes and a maximum time of 67 minutes.

Part of the problem in producing concrete with adequate properties and also with pumping, likely resulted from an overestimation of the free-surface moisture on the aggregates, particularly the manufactured sand and possibly the natural sand. As discussed in Lindquist et al. (2008), the corrected actual *w/c* ratio for the mixtures placed on September 29, 2007, may realistically have been 0.37 as compared to the design *w/c* ratio of 0.42.

The contractor decided to switch to the Alternate Mixture, but the electrical outage at the concrete plant occurred before any loads of the Alternate Mixture could be batched. All the concrete in the first placement was the initial mix designed with KU Mix.

Concrete was placed in the deck with a large, 47-m (154-ft) pump which operated at a lower pressure than the smaller 17-meter (56-ft) pump used for the qualification slab. The contractor had great difficulty pumping the concrete. The pump operated above the recommended pressure levels and clogged several times throughout the night. The pump operator noted that a pump pressure of 220 bars (47 psi/bar) is desirable, and that the pumps were operating at about 265 bars and saw a maximum of about 325 bars. At the second placement, the pump operator noted that the pump had been new and that the o-rings needed to be replaced after the first placement. At the truck discharge into the pump, the low-slump concrete did not pass through the grate, so it was removed. Coarse aggregate particles removed from the pump hopper were later tested and did not pass the 38-mm (1½-in.) sieve. An air cuff was used at the pump discharge on the deck to limit air loss.

As mentioned previously, placement was from south to north, from Pier 4 toward the north abutment. The placement stopped at a header located just past (to the north of) Pier 3. Hand vibrators were used to consolidate the concrete in the first few feet of the deck at Pier 4. Finishing was completed with a single-drum roller screed and a bullfloat. Occasionally a wooden float was also used. Consolidation and strike-off operations proceeded while the concrete was pumped, but the finishers needed to work the surface 4 or 5 times to get a smooth surface due to the concrete stiffness and long delays. Because a smooth surface was difficult (or impossible) to achieve, the finishers wanted to use water as a finishing aid. Delays, totaling about 1.5 hours due to concrete that did not meet specifications and was difficult to pump, resulted in significant finishing delays. Locations with significant pockets and divots were observed after the curing period was completed and the curing materials were removed. As finishing operations began after delays, the finished concrete that was not covered with burlap was bullfloated a second time.

Fogging was used extensively during the first placement, especially during the delays due to concrete pumping problems.

Burlap was placed using two access bridges following the finishing bridge. The first bridge was also used for bullfloating. Burlap placement times ranged from 7 to 13 minutes, not including three delays of 15, 35, and 40 min., with an average placement time of 9 minutes. The contractor did an excellent job of keeping the burlap wet with a spray hose after it was placed.

On October 1, 2007, the day before the evening of placement 2, the ready-mix supplier and the pumping company voluntarily pumped a trial batch of the Alternate Mix with KU personnel on site. The trial batch met the specifications for concrete temperature [19°C (67°F)] and slump [100 mm (4 in.)] but did not meet specifications for air content (11.4%). KU personnel expressed concern that they were testing pumpability using a batch that did not meet specifications and has significantly higher slump than the low slump concrete on placement 1. The concrete pumped with no problems using a 47-m (154-ft) pump truck with the boom extended vertically. Two of the same types of pumps were going to be present at the second placement that night. The pump did not have any device to limit air loss, and the air content at the end of the pump discharge was 9.5%.

Deck Placement 2 (10/2/2007). LC-HPC-4 was completed with a second placement on October 2, 2007, with construction starting at 1:00 a.m. Air temperatures during the placement ranged from 18.8º to 19.4ºC (66º to 67ºF), with a minimum and maximum for the day of 12º and 27ºC (54º and 81ºF).

The contractor used the Alternate Mix (*w/c* ratio = 0.42) containing less manufactured sand and used a lower free-surface moisture content correction to determine batch weight. Pumping was much easier than had been for placement 1 and the placement was completed successfully by approximately 6:00 a.m.

Concrete test results indicated that all of the concrete tested for placement 2 met the specifications for slump, ranging from 35 mm (1.4 in.) to 100 mm (4 in.), with an average of 78 mm (3.1 in.). Air contents ranged from 6.8% to 10.4% with an average of 8.6%. Three of the 12 truckloads tested for air content exceeded the maximum allowable, with air contents of 10.4%, 9.8%, and 9.6%. There was some confusion with the KDOT testing crew whether to test the next truck after a truck tested to not meet specifications or to wait for the next standard test. The crew did not want to test the next truck because they were already working very quickly to keep up with the specified testing rate. A clear lesson is that a plan for testing and how to handle these types of situations should be reviewed prior to the start of placement. The first concrete was tested before and after the pump, showing an air loss of 2.0%. Subsequent concrete testing occurred at the truck and three samples were tested for air content on the deck after the pump (7.0%, 9.0%, and 7.2%). These three samples do no correspond directly to any of the testing performed at the trucks, so air loss cannot be determined. It is clear that all three samples on the deck met the specifications for air content. The concrete surface temperatures ranged from 15ºC (59ºF) to 22ºC (71ºF) with an average of 18ºC (64ºF). Standard ASTM C 1064 concrete temperature testing was not performed for this placement. Chilled water and ice were used to control the concrete temperature. Initially, the amount of water replaced with ice was high, causing the concrete at the plant to not achieve realistic slump measurements because the ice was not melted. Later, the supplier reduced the amount of ice and used more chilled water instead, causing the ice to melt faster and helping the supplier to better evaluate and control the slump before the truck left the plant. The day after the deck was placed, the concrete supplier indicated that the large quantity of ice had been part of the problem with controlling the slumps and that minimal ice and more chilled water is preferred. Superplasticizer was added directly to the first eight trucks on site. Strength cylinders were cast from the concrete in first truck, after the pump. Also, part way through the placement, the free-surface moisture contents of the aggregates used to calculate batch weight was changed; a second set of cylinders was cast after the change, but from concrete out of the back of the truck.

The haul time from loading to discharge for every truck was recorded as 60 minutes, calling into question the validity of this figure.

Concrete was placed in the deck with the same size pumps tested the day before. It was much easier to pump than for placement 1. An S-Hook or other device was not used at the end of the pump to restrict air loss through the pump.

Placement was from south to north again, from the header (just north of Pier 3) to the north abutment.

The concrete was finished using a single-drum roller screed and a bullfloat. Fogging was not used for this placement, and the maximum evaporation rate was very low, only 0.04 kg/m^2/hr (0.008 lb/ft^2/hr). There was a delay at the end of the deck due to concrete delivery. The contractor was asked to turn on the fogging, but did not because they would have had to restart the finishing equipment to turn on the foggers. The fogging equipment should be functional for the entire placement.

Burlap was lifted by crane to the deck on pallets and unloaded onto two work bridges. Two layers of burlap were placed at the same time and each piece of burlap was approximately half the width of the deck in length. The burlap placement was somewhat slow, consistently 10 to 15 minutes behind the finishing bridge. Burlap placement for the last 25 feet of the deck was delayed due to concrete delivery, as mentioned before. This portion of the deck remained exposed with no fogging for about 40 minutes after finishing. All the burlap was kept wet with a spray hose just after placement. The average time between finishing and burlap placement was 16 minutes, with a minimum time of 7 minutes and a maximum time of 43 minutes. Seventeen of 23 (74%) locations timed exceeded the 10 minute requirement, with times ranging from 12 to 43 minutes.

Form removal was completed for LC-HPC-4 on day 27 after placement.

Unique Considerations. LC-HPC-4 was a super-elevated flyover bridge. Besides pumping, placement of concrete by buckets was the only other option which, because it is slower, may have required sequential placements to complete the bridge deck.

Manufactured sand was used for this project. Two mixtures were prequalified and both pumped adequately at the qualification slab. The manufactured sand, a change in the pumping equipment, and overestimation of the free surface moisture on the aggregates lead to significant pumping difficulties during the first placement. The contractor believed the pumping difficulties were due to the mixture containing a larger percentage of the manufactured sand and switched to the mixture containing less manufactured sand for the second placement. A lower and more realistic value for the free-surface moisture on the aggregate was used for the batch calculations.

An air cuff was used for placement 1, but not for placement 2. At the trial batch between the two placements, the contractor said they would no longer allow an attachment (such as an "S-Hook") on the end of the pump discharge for safety. He said that a large steel attachment swinging at the end (discharge) of the pump hose posed a hazard for workers. The latest (2009) LC-HPC specifications now require the use of an air cuff on pumps. An air cuff is typically located higher on the pump discharge than an end attachment and does not pose a safety concern for workers on the deck.

The concrete for placement 2 was cast in direct contact with placement 1 during the placement 1 curing period. It is likely that a portion of the placement 1 curing material was removed to facilitate the construction of placement 2. It is unclear how long and how large of an area in placement 1 was left exposed for the purpose of casting placement 2, or what efforts, if any, were made to keep the exposed portions of placement 1 wet.

Response from Personnel and Post-Construction Conference (5/28/2008). On 11/29/2008, a KDOT inspector indicated that the larger divots on this bridge from placement 1 would need to be filled.

During placement 2, there was some confusion with the KDOT testing crew whether to test the next truck after a truck tested to not meet specifications or to wait for the next standard test. The crew did not want to test the next truck because they were already working very quickly to keep up with the specified testing rate.

The contractor did not want to turn on fogging equipment during the delay at the end of placement 2 because it would require turning on the finishing equipment again.

The post construction conference was held on May 28, 2008, nearly eight months after the completion of LC-HPC-4. The conference also covered the three other LC-HPC decks in the contract (LC-HPC-3, 5, and 6), which were constructed in that period. The responses at that conference where reflective of the experiences of the whole project (all four bridges) and are reviewed in Section 5.3.16.

Lessons Learned. The concrete supply is critical to the successful completion of a deck placement.

Manufactured sand has a negative impact on the pumpability of low-paste content LC-HPC mixtures.

Using ice at a high rate of replacement can cause some difficulty in controlling concrete properties, slump in particular. Less ice and more chilled water is preferable, which means that from the concrete supplier's point of view, cooler weather is preferable.

The qualification slab did not meet the placement time requirements for any point timed along the slab. Placement of LC-HPC-4 did not go smoothly, particularly from a concrete production standpoint. The contractor's request for the qualification slabs for LC-HPC-3, 5, and 6 to be waived, should have been reconsidered and a second qualification slab required for the contract. In addition, consideration should be given to instituting minimum requirements for a qualification slab before another qualification slab may be considered to be waived. For example, a qualification slab placement should meet specifications for burlap placement at a minimum of 50% of the number of stations timed, and 70% of the truckloads placed in the qualification slab must meet specifications for all plastic concrete requirements. Such guidelines may prove to be beneficial for determination of whether a qualification slab may be waived, especially due to unforeseen differences between projects and materials, instead of solely relying on previous contractor experience.

After the pumping difficulties on placement 1, the contractor retested the pumpability of the new mixture prior to the second placement. This was a good idea, but should have been done on concrete that met all of the specifications.

Prequalification of two mixtures may not be a good idea. The qualification slab should be placed using only one concrete mixture so that the supplier can gain experience producing multiple and successive batches of the concrete before the deck placement.

A plan for testing, how to handle trucks that do not meet specification, and requirements for testing of subsequent trucks should be established early in the project and reviewed with the testing crew just prior to the start of placement.

5.3.14 LC-HPC Bridge 6

LC-HPC-6 is part of the major I-435 contract in Kansas City discussed previously in Section 5.3.13. It is the eighth LC-HPC deck constructed in Kansas and the second LC-HPC deck constructed in the contract. LC-HPC-6 is the second (northeast) unit of the southbound US-69 to westbound I-435 flyover ramp. Practically, when traveling south on US-69 and taking the I-435 west exit, LC-HPC-6 is the first portion of the flyover ramp after the west exit splits from the east exit.

The qualification batch and slab, as well as the post construction conference, are the same as for LC-HPC-4 (Section 5.3.13). The bridge deck was completed on November 3, 2007. Dates related to the construction of LC-HPC-6 are shown in Table 5.14.

Table 5.14 – Construction Dates for LC-HPC-6

Item Constructed	Date Completed
Qualification Batch – same as LC-HPC-4	6/7/2007
Qualification Slab – same as LC-HPC-4	9/14/2007
LC-HPC Deck	11/3/2007
Post-Construction Meeting – same as LC-HPC-3, 4, and 5	5/28/2008

Design. LC-HPC-6 is the second unit (the northeast unit) of the southbound US-69 ramp bridge to I-435 west. Spanning from Pier #4 to Pier #6b, it is a four-span, super-elevated (7.3%), curved, steel plate-girder bridge with non-integral end conditions, and jersey barriers. The south side of the deck is raised on this superelevated roadway. There is an expansion joint between LC-HPC-6, the second unit of the bridge, and LC-HPC-5, the first unit of the bridge.

The whole bridge, LC-HPC-6 (Unit 2) and LC-HPC-5 (Unit 1) together, is 350.85 m (1150.8 ft) long, with LC-HPC-6 being 181.0 m (593.8 ft) long and LC-HPC-5 being 169.0 m (554.5 ft) long. The four span lengths (deck lengths) for LC-HPC-6, from the Pier # 4 expansion joint to Piers #5, #6, #7, and #6b are 39.79 m (130.5 ft), 51.0 m (167.3 ft), 51.0 m (167.3 ft), and 38.91 m (127.7 ft).

The total width of LC-HPC-6 is 8.73 m (28.6 ft). The LC-HPC-6 deck is monolithic with a total depth of 220 mm (8.7 in.), 75 mm (3 in.) of top cover, and 30 mm (1.2 in.) of bottom cover. The top mat of reinforcing steel consists of No. 19 (No. 6) bars spaced at 180 mm (7.1 in.).

Concrete. As discussed in Section 5.3.13, the concrete continued to be the most challenging aspect of the construction for this set of bridges, and LC-HPC-6 was no exception.

The Alternate Mix described in Section 5.3.13 was modified for use in LC-HPC-3, in that the *w/c* ratio was increased to 0.45. This change was made by the contractor with approval from the KDOT Olathe office, but KU personnel were not informed. A cement content of 317 kg/m^3 (535 lb/yd^3) was used for the entire deck placement. A high-range water reducer was used instead of a mid-range water reducer. The free-surface moisture for the manufactured sand was reported as 5.8%, higher than for the second placement of LC-HPC-4.

Fordyce Concrete, located approximately 27 km (16.8 mi) from the bridge, provided the concrete for LC-HPC-6. The average time from loading to discharge for the deck placement was 62 minutes, with a maximum time of 113 minutes and a minimum time of 38 minutes.

Control of concrete properties was a struggle for this placement, as described below. Pumping did not appear to be as big of a challenge as for LC-HPC-4.

Qualification Batch (6/7/2007). The qualification batch was the same as for LC-HPC-4 described in Section 5.3.13.

Qualification Slab (9/14/2007). The qualification slab was the same as for LC-HPC-4 described in Section 5.3.13.

Deck Placement (11/3/2007). The placement of LC-HPC-6 occurred on November 3, 2007, with construction starting at approximately 5:20 a.m. The last burlap was placed at 12:30 p.m., for a total time of just over 7 hours. The average placement rate for the placement was approximately 48 m^3/hr (63 yd^3/hr). Air temperatures during the placement ranged from 2 to 13ºC (36 to 55ºF), with a minimum and maximum air temperature of 2º and 18ºC (35º and 65ºF) according to weather station data. Because the air temperature was expected to drop below 4ºC (40ºF) during the curing period, the girders and deck were wrapped and heated during the curing period to meet the requirements for the cold weather curing to maintain the deck and girders at temperatures of 13º to 24ºC (55º to 75ºF). Air temperatures dropped below freezing on days 3 and 4 of the 14-day curing period, and below 4ºC (40ºF) on 11 of the 14 days. At the time of placement, just less than half of bridge had been wrapped, from Pier #4 to about 6.1 m (20 ft) west of Pier #6, as shown in Fig. 5.30 a and b. The remainder of the bridge was wrapped after the placement. The method of wrapping the girders is shown in Fig. 5.31.

Fig. 5.30 (a) Pier #4

(b) Pier #5 to just west of Pier #6

Fig. 5.30 Portions of LC-HPC-6 were wrapped for heating during the curing period.

Fig. 5.31 Girders wrapped for cold weather curing requirements.

As described, control of concrete properties was a struggle for the placement of LC-HPC-6. Concrete testing was performed out of the truck and the air content was rechecked on the deck (pump discharge) for trucks that were accepted with air content above the specifications. Multiple truckloads of concrete with properties that did not meet the specifications were accepted and placed in the deck, and only one truckload was rejected near the end of the deck.

The first truckload was tested at the truck and after the pump, with discharge on the ground, not to the elevated deck. The air loss was measured to be 2.9%. KDOT inspectors used this measurement of the air loss through the pump to estimate the air content at the discharge to the deck. This was not appropriate because the elevation of the pump discharge can significantly affect the amount of air loss. Only two of the first three truckloads were tested (at the truck), and neither met specifications for slump [107 and 120 mm (4.2 and 4.7 in.)] or air (9.9% and 11.5%). Even though they did not meet specifications, KDOT personnel allowed these truckloads to be placed in the deck based on the air loss measurement on the first truckload and did not require testing of the third truck.

Concrete test records indicate that for concrete placed in the deck, the air contents as tested from the trucks ranged from 7.5% to 11.5%, with an average of 9.5%. For concrete placed in the deck, eight of the 13 air content tests performed at the truck did not meet the specifications for air content. For three of these tests, the concrete was retested on the deck after the pump. In total, five air content tests were performed on the deck, of which one did not meet specifications (6.0% air). Air loss for the two air-loss measurements performed during the first three-quarters of the placement (approximately equivalent to the length of the deck pumped without an air air cuff), were 1.4% and 1.0%, corresponding with the portion of the deck that was placed with no air cuff. The air loss for the one test performed on the last quarter of the deck was 0.6%, corresponding with the portion of the deck that was placed using an air cuff.

For concrete placed in the deck, the slump as tested from the trucks ranged from 60 to 140 mm (2.25 to 5.5 in.), with an average of 96 mm (3.75 in.). Concrete was not retested for slump at the pump discharge (on the deck) because the testing crew only had one slump cone. This significantly limited the ability of inspectors to ensure that the concrete placed in the deck met specifications. One truckload had high slump [110 mm (4.3 in.)] and was held for 40 minutes and then placed in the deck without retesting.

The concrete surface temperature ranged from 11º to 18ºC (52º to 64ºF) with an average of 15.5ºC (60ºF). No measures were required to control the concrete temperature. ASTM C 1064 concrete temperature testing was not performed for this bridge deck.

Communication between KU personnel and the KDOT testing crew was challenging. It was observed that communication within the KDOT testing crew was also difficult and deteriorated through the night as crew members became tired, which was likely the cause for communication difficulties with KU personnel. When concrete went out of specification, KDOT personnel were reluctant or unwilling to require the contractor to adjust the mix. As a result, at KU's request, the senior

KDOT technician established maximum limits for acceptance, but subsequent trucks with high slump were accepted. KU personnel believe that many slump measurements were reported without careful inspection of the ruler, and the reported values appear to have been erroneous (reported too low). The concrete supplier representative was not always present and had to be located when the concrete went out of specification.

Placement was from west (Pier #4) to (north) east (Pier #6b). Pumping appeared to be better than for LC-HPC-4. Two pumps were used to place concrete in the elevated deck. The first pump used on the deck did not have an air cuff at the pump discharge, as shown in Figs. 5.32(a) and (b). This pump was used from Pier #4 until just past, to the north (east) of, Pier #7. The second pump, used for the last span of the placement, had an air cuff at the pump discharge, as shown in Figs. 5.32(c) and (d). Only one span the northeast span was placed using an air cuff to control air loss.

Fig. 5.32 (a) First pump did not have an air cuff

Fig. 5.32 (b) First pump (with no air cuff) was used until approximately Pier #7

(c) Second pump had an air cuff to control air loss

(d) Second pump used for last portion of the deck while the first pump is departing the site

Fig. 5.32 Two different pumps used for the placement of LC-HPC-6, the first with no air cuff and the second had an air cuff to limit air loss

There was a delay in the placement while moving the second pump because a front loader had overturned, blocking the narrow path. Once the pump was moved, concrete delivery for this location was slow because only one concrete truck could use the narrow path at a time. Each truck waited until the previous truck unloaded and backed out from the pump. The delays did not exceed 20 minutes.

The gang vibrators consisted of 11 vibrators mounted together on the finishing bridge. The concrete was finished using a single-drum roller screed and a bullfloat. The concrete did not finish as well as for other placements, and the surface contained voids, with larger voids near the end of the placement. KDOT did not appear to be concerned about the finish.

There were several delays during placement because of concrete delivery and and pump trucks moving locations. Fogging was used whenever there was a delay of more than 10 minutes.

Burlap placement was efficient for LC-HPC-6. Rolls of presoaked burlap were lifted to the deck by crane and placed in the same manner as for LC-HPC-4.

The average time between finishing and burlap placement was 7 minutes, with a minimum time of 2 minutes and a maximum time of 20 minutes. Fourteen of 87 (16%) locations timed exceeded the 10 minute requirement, with times ranging from 11 to 20 minutes. The locations where the burlap was not placed within 10 minutes often corresponded with delays caused by slow concrete delivery. The in-place burlap was kept wet using hoses to spray the burlap within about 30 minutes after it was placed. The burlap remained wet for the entire placement at all locations checked.

Response from Personnel and Post-Construction Conference (5/28/2008). The attitudes of the KDOT testing crew proved to be a significant barrier for successful enforcement of concrete specifications. Communication between KU personnel and the KDOT testing crew was very challenging and new lines of communication through senior KDOT technicians needed to be established during placement to respond to out of specification concrete. These efforts were only marginally successful.

The post construction conference was held on May 28, 2008, nearly seven months after the completion of LC-HPC-6. The conference also covered the three other LC-HPC decks in the contract (LC-HPC-3, 4, and 5). The responses at that conference where reflective of the experiences of the whole project (all four bridges) and are reviewed in Section 5.3.16.

Lessons Learned. Testing crews should have duplicates of all testing equipment, particularly for elevated deck placements where testing may be required on samples taken from different locations.

It is important to work with each new set of testing personnel so they understand the importance of the new procedures and are on-board with enforcing the specifications.

It is important to have an inspector visually checking each truck as it is accepted. Truckloads with high slump may be identified and addressed that would otherwise be placed in the deck.

Clear lines of communication between contractor, supplier, and testing personnel are vital for the successful completion of LC-HCP construction.

It is necessary to establish guidelines before placement for rejecting concrete trucks and handling trucks that do not meet the specifications.

5.3.15 LC-HPC Bridge 3

LC-HPC-3 is part of the major I-435 contract in Kansas City, as discussed in Section 5.3.13. It is the ninth LC-HPC deck constructed in Kansas and the third LC-HPC deck constructed in the contract. LC-HPC-3 is the westbound 103rd Street bridge over US-69 in Kansas City. The companion structure, the eastbound bridge at the same location, serves as Control 3. The two bridges are independent structures but they are in contact at a joint.

The qualification batch and slab, as well as the post construction conference, are the same as for LC-HPC-4, as discussed in Section 5.3.13. The bridge deck was completed on November 13, 2007. Dates related to the construction of LC-HPC-3 are shown in Table 5.15.

Table 5.15 – Construction Dates for LC-HPC-3

Item Constructed	Date Completed
Qualification Batch – same as LC-HPC-4	6/7/2007
Qualification Slab – same as LC-HPC-4	9/14/2007
LC-HPC Deck	11/13/2007
Post-Construction Meeting – same as LC-HPC-4, 5, and 6	5/28/2008

Design. LC-HPC-3 is the westbound bridge on 103rd Street over US-69. It is a four-span, steel plate-girder bridge with non-integral end conditions, a 6 degree skew, and solid corral rail barriers between the north side of the deck and the sidewalk.

LC-HPC-3 is 115.91 m (380.3 ft) long. The four span lengths are 22.2 m (72.9 ft), 35.3 m (115.8 ft), 35.3 m (115.8 ft), and 22.2 m (72.9 ft). The total width of LC-HPC-3 is 15.21 m (49.9 ft). The LC-HPC-3 deck is monolithic with a total depth of 220 mm (8.7 in.), 75 mm (3 in.) of top cover, and 30 mm (1.2 in.) of bottom cover. The top mat of reinforcing steel consists of No. 16 (No. 5) bars spaced at 160 mm (6.3 in.).

Concrete. The modified Alternate Mix used for LC-HPC-6 was again used for LC-HPC-3, with a *w/c* ratio of 0.45 and a cement content of 317 kg/m^3 (535 lb/yd^3) for the entire deck placement. A high-range water reducer was used instead of a mid-range water reducer. The free-surface moisture for the manufactured sand ranged from 3.9% to 4.5%.

Fordyce Concrete, located approximately 27 km (16.8 mi) from the bridge provided the concrete for LC-HPC-3.

Clear guidelines for concrete testing and acceptance were established prior to placement. The rule was simple: no concrete with slump greater than 100 mm (4 in.) or air content greater than 9.5% would be placed in the deck. The concrete was sampled from the ready-mix trucks to ensure that all concrete placed in the deck met specifications. Truckloads that did not meet specifications would either be rejected or set aside and retested prior to placement in the deck. Five trucks for which initial test results did not meet the specifications were held and retested after a period of waiting. All of these truckloads, upon retesting, met specifications and were placed in the deck. The establishment of clear guidelines and clear communication with the KDOT inspectors and testing crew prior to the placement eliminated the ambiguity that existed with the testing crew on acceptance criteria for the LC-HPC-4 and 6 placements, and improved communication with the testing crew from LC-HPC-6 placement.

The last two truckloads tested for air content did not meet the specifications, with air contents of 10.5% and 10.1%. These were accepted by KDOT inspectors and placed in the deck. The first of these two (air content 10.5%) was tested on the deck, with an air content of 9.0%, indicating a 1.5% loss in air. Air loss for the other two tests was 1.6% and 1.1%. An air cuff was used at the pump discharge to limit air loss through the pump. Pumping was acceptable for LC-HPC-3.

Qualification Batch (6/7/2007). The qualification batch was the same as for LC-HPC-4 described in Section 5.3.13.

Qualification Slab (9/14/2007). The qualification slab was the same as for LC-HPC-4 described in Section 5.3.13.

Deck Placement - (11/13/2007). The placement of LC-HPC-3 occurred on November 13, 2007, with construction starting at 2:00 a.m. The last burlap was placed at 9:30 a.m., for a total time of 5.5 hours. The average placement rate for the placement was approximately 71 m^3/hr (93 yd^3/hr). Air temperatures during the placement ranged from 6 to 12ºC (43º to 54ºF), with a minimum and maximum air temperature for the day of 4º and 19ºC (39º and 66ºF) according to weather station data. Air temperatures dropped below freezing on days 9 through 14 of the 14-day curing period, and below 4ºC (40ºF) on 13 of the 14 days. The girders were wrapped and heated as required by the specifications for cold weather curing.

Concrete test records indicate that the slump ranged from 45 to 100 mm (1.75 to 4.0 in.) with an average of 83 mm (3.3 in.). Air contents ranged from 6.5% to 10.5%, with an average of 8.6%. As discussed previously, the last two tests indicated the air content was above the maximum allowable. These tests were repeated after the pump and the concrete met specifications. At the end of the placement, KU learned that all the air content test records did not have the aggregate correction factor taken into account, meaning that the actual air contents were slightly below the recorded values. The concrete surface temperature ranged from 11º to 17ºC (52º to 62ºF) with an average of 14ºC (58ºF). The standard ASTM C 1064 temperature test was not performed for this placement. The clearly outlined testing and acceptance strategy described previously was successful. As mentioned previously, testing was performed on concrete sampled directly from the ready-mix trucks. There was one delay in the concrete delivery due to a compressor failure at the ready-mix plant.

The direction of placement was from east to west. The concrete was placed in LC-HPC-3 by pumping with two pump trucks, one positioned below each end of the bridge. The concrete pumped adequately, with average air loss through the pump of 1.5%, and no slump loss.

The concrete was finished using a single-drum roller screed and a bullfloat. The contractor complained about the deck surface not finishing well and wanted to use water as a finishing aid. The KDOT inspector instructed the contractor to finish the surface to the best of his ability, working the surface as much as they like, but to not use water. The contractor used the bullfloat to work the surface considerably and the final finish appeared to be approximately the same as for other LC-HPC decks. Water was used as a finishing aid for approximately (50 ft) of the sidewalk before this was stopped.

Fogging was never used. The fogging system was different than the system qualified at the qualification slab. The nozzles were connected with a rubber hose and not the galvanized piping for the qualified system. The maximum evaporation rate was just 0.017 kg/m^2/hr (0.034 lb/ft^2/hr).

Burlap was pre-positioned along the deck, hanging over the roadway barrier with soaker hoses tied to it to maintain saturation. The burlap was placed from the second and third work bridges. Forward progress of the finishing and burlap placement seemed to be slower than for other placements as the consolidation and finishing equipment often caught up with the concrete deposited in front of the screed, causing finishing operations to pause and wait for the concrete. The slower burlap placement may have been due to the wider deck, and also because the burlap placement crew was not the same as for the qualification slab. The average time to burlap placement was 15 minutes, with a minimum of 9 minutes and a maximum of 25 minutes. Only two of 22 locations timed along the deck met the 10-minute specification requirement. There were two delays (4 and 10 minutes) due to concrete delivery to the deck. Two layers of burlap were placed simultaneously. The burlap placement crew consisted of ten workers: 4 workers on the work bridges placing burlap, 4 workers on the sides of the deck pushing the work bridges, and 2 workers delivering burlap to the work bridges.

The burlap was maintained in a wet condition by spray hoses for some of the deck, and by soaker hoses for the middle portion of the deck. The spray hoses seemed to be more effective. At noon, at two locations along the deck, the burlap covering the barrier steel was found to have blown off, leaving approximately 0.2 m^2 (2 ft^2) of concrete deck exposed at each location. Water was found to be flowing over the surface of the concrete. The burlap covering the barrier steel was dry. Workers were instructed to tie together the pieces of overlapping burlap that covered the barrier steel so that they would not blow off again.

Prior to placement, the contractor approached KU personnel refusing to cover the sidewalk portion of the placement with burlap immediately after finishing because they did not want to disturb the finish. The contractor wanted to use a curing compound and delay burlap placement. KU indicated that curing compounds were not allowed and that the surface must be maintained in the wet condition. The workers were told to spray water on the surface of the finished sidewalk every 10 minutes and that the surface must always look shiny and wet. Considerable effort was required to continuously inspect the sidewalk and remind workers to rewet the surface. The first burlap on the sidewalk was placed on the east end approximately two hours after finishing. After that, burlap placement on the sidewalk was much faster, and by the end of the placement (the west end of the sidewalk), the burlap was placed within 20 to 30 minutes after finishing.

The sidewalk was hand vibrated, then strike-off was completed by hand with a 2×4, the surface was bullfloated, then hand trowled, and the final surface finish was applied with a broom. Because the contractor was concerned about marring the sidewalk finish, the workers placed the burlap on the sidewalk to avoid (minimize) touching the surface of the deck. To do this, the burlap was placed over the barrier reinforcing steel and placed on the deck away from the location where the reinforcing steel contacts the deck, creating a burlap "tent" and leaving a gap at the base of the reinforcing steel where the burlap was not in contact with the deck. Soaker hoses were placed on the sidewalk (approximately in the middle) immediately after the burlap was placed. Water was observed flowing over the sidewalk surface even in areas where the burlap was not in contact with the concrete (under the burlap tent). Two workers were assigned to the sidewalk burlap placement and rewetting.

It was observed from photographs that runoff water from the soaker hoses positioned on the burlap that covered portions of the sidewalk was likely worked into the surface of the sidewalk during finishing operations, as shown in Fig. 5.33.

Fig. 5.33 Water worked into surface of the sidewalk

Because the bridge had non-integral end conditions and there was no abutment to fill, the finishing bridge was removed quickly from the deck and there was no delay in burlap placement at the end of the deck.

According to construction diaries, deck forms were removed on November 26, 2007, thirteen days after placement and one day before the required 14-day curing period was completed.

On November 29, 2007 the application of the curing membrane was observed. This implies that curing was removed sixteen days after placement, providing two days of curing more than required by the specifications. For the curing membrane, a pink curing compound (not opaque) was applied. There was good coverage of the deck with two passes made at perpendicular angles. After completion, the applicaton appeared uneven. However, the darker areas on the deck surface were due to the overlap of material application resulting in additional material in the areas of application overlap, and not because of insufficient application of material. Four passes, or twice as much curing membrane material as required, was applied in these overlapped sections. An electric compressor sprayer was used instead of the typical 3-gallon hand sprayer. Therefore, the application was faster than obtained with standard procedures. KDOT inspectors indicated that the pink color can be seen for about three days. After that time, the inspector must be aware of any construction activities that might damage the membrane. During application of the curing membrane, burlap was placed at the base of the barrier steel to prevent the curing membrane from coating the reinforcing steel. Burlap covered 3 to 4 inches of the deck closest to the barrier reinforcing steel.

The inspector indicated that the minor divots in the deck surface will be acceptable after grooving.

Unique Considerations. The contractor objected to covering the sidewalk with burlap because he was concerned about marring the surface finish (broom finish). The sidewalk was kept wet by hose misting every 10 minutes while it was uncovered. Considerable inspection was required to ensure that the surface always looked shiny. The sidewalk at the east end of the deck was left uncovered for nearly two hours. The contractor started covering the sidewalk more quickly as the placement proceeded, so the sidewalk at the west end was covered within 20 to 30 minutes after strike-off.

On November 29, 2007, after the curing period was complete, the wearing surface of the sidewalks was observed, and the two ends of the deck compared. A KDOT inspector indicated that the final surface finish (broom finish) was apparent and acceptable for both ends of the sidewalk (the finish was approximately the same for the two ends). Observations of the sidewalk finish during a crack survey completed on June 5, 2009 indicated no difference in the finish between the west and the east ends of the sidewalk on LC-HPC-3. In addition, there was also no significant difference in the sidewalk finish for LC-HPC-3 compared with the sidewalk finish for the companion and control structure, Control 3, the eastbound bridge at the same location.

After the 14-day curing period was completed, the application of the curing compound was observed. The coverage was complete, but appeared to be uneven due to thicker material in the overlap areas, not because of insufficient application of the material.

Response from Personnel and Post-Construction Conference (5/28/2008). KDOT personnel indicated that placement of elevated decks such as this one could be done by bucket if the placements were done sequentially as allowed in the plans. He indicated that pumping is faster and more convenient, but not absolutely mandatory for elevated decks.

The post-construction conference for LC-HPC-3, 4, 5, and 6 occurred on May 28, 2008. The results are summarized in Section 5.3.16, which covers LC-HPC-5, the last bridge to be completed in this group.

Lessons Learned. It is not possible to control the response and actions of the contractor in the field. Maintaining open lines of communication, especially for unforeseen issues (such as the sidewalk in this case), is vital to the successful implementation of the project. In this case, maintaining the moisture of the sidewalk concrete was achieved, though the time to burlap placement was not.

If the deck has some surface imperfections after finishing is competed, minor surface divots can be acceptable after grooving operations are completed.

The broomed surface finish was not significantly impacted by the early application of wet burlap on finished concrete before set has occurred.

5.3.16 LC-HPC Bridge 5

LC-HPC-5 is one of the bridges in the major I-435 contract in Kansas City, as discussed previously in Section 5.3.13. It was the tenth LC-HPC deck constructed in Kansas and the fourth (and last) LC-HPC deck constructed in the contract. LC-HPC-5 is the first (west) unit of the southbound US-69 to westbound I-435 flyover ramp. When traveling south on US-69 and taking the I-435 west exit, LC-HPC-5 is the last portion of the flyover ramp, just before entering I-435 west.

The qualification batch and slab, as well as the post construction conference, are the same as for LC-HPC-4, as discussed in Section 5.3.13. The bridge deck was completed on November 14, 2007. Dates related to the construction of LC-HPC-5 are shown in Table 5.16.

Table 5.16 – Construction Dates for LC-HPC-5

Item Constructed	Date Completed
Qualification Batch – same as LC-HPC-4	6/7/2007
Qualification Slab – same as LC-HPC-4	9/14/2007
LC-HPC Deck	11/14/2007
Post-Construction Meeting – same as LC-HPC-3, 4, and 6	5/28/2008

Design. LC-HPC-5 is the first (west) unit of the southbound US-69 ramp bridge to I-435 west and goes from the west abutment to Pier #4. It is a four-span, super-elevated (7.3%), curved, steel plate-girder bridge with non-integral end conditions, and jersey barriers. The south side of the deck is the superelevated side.

There is an expansion joint between LC-HPC-5, Unit 1, and LC-HPC-6, Unit 2 of the same bridge.

The whole bridge, LC-HPC-6 (Unit 2) and LC-HPC-5 (Unit 1) together, is 350.85 m (1148.3 ft) long; LC-HPC-5 is 169.0 m (554.5 ft) long, and LC-HPC-6 is 181.0 m (593.8 ft) long. The four span lengths (deck lengths) for LC-HPC-5, from the west abutment to the expansion joint at Pier # 4, are 29.37 m (96.4 ft), 50.0 m (164.0 ft), 50.0 m (164.0 ft), and 39.91 m (131.0 ft).

The total width of LC-HPC-5 is 8.73 m (28.6 ft). The LC-HPC-5 deck is monolithic with a total depth of 220 mm (8.7 in.), 75 mm (3 in.) of top cover, and 30 mm (1.2 in.) of bottom cover. The top mat of reinforcing steel consists of No. 19 (No. 6) bars spaced at 180 mm (7.1 in.).

Concrete. As discussed in Sections 5.3.13 through 5.3.15, the concrete continued to be the most challenging aspect of the construction for this set of bridges, and LC-HPC-5 was no exception.

The original mix design for LC-HPC-5 included a *w/c* ratio of 0.42, the same as originally specified for LC-HPC-4, 5, and 6. The day prior to the LC-HPC-5 deck placement, LC-HPC-3 and the qualification slab for LC-HPC-14 had been placed with a *w/c* ratio of 0.45, as described in the corresponding sections. During the LC-HPC-14 qualification slab, KU personnel learned that the *w/c* ratio for the I-435 bridges LC-HPC-3 and 6 had been changed, by the contractor (with permission from KDOT Olathe office) from 0.42 to 0.45. Because the 0.42 *w/c* ratio concrete originally intended for LC-HPC-3, 4, 5, and 6 had been placed successfully at both LC-HPC-4 placement 2 (on October 2, 2008) and at the qualification slab for LC-HPC-14 (on November 13, 2009), the decision was made to change back to the 0.42 *w/c* ratio mixture for the LC-HPC-5 placement.

Without consultation, the contractor and concrete supplier switched mix designs several times during the placement of LC-HPC-5, including at times, the addition of water on site prior to testing and without approval or communication with KDOT or KU personnel, which had been clearly forbidden. The Alternate Mix was initially used and then changed throughout the placement with reported *w/c* ratios ranging from 0.42 to 0.45. The first seven truckloads had a *w/c* ratio of 0.42. The next 17 truckloads had a *w/c* ratios of approximately 0.43. The last 24 truckloads had a *w/c* ratio of 0.45. The cement content of the concrete remained at 317 kg/m^3 (535 lb/yd^3) for the entire deck placement. In the end, four different mix designs were used in the deck. A high-range water reducer was used instead of a mid-range water reducer. The free-surface moisture for the manufactured sand was set at 4.5% for the entire placement.

Fordyce Concrete, located approximately 27 km (16.8 mi) from the bridge, provided the concrete for LC-HPC-5. The average time from loading to discharge was 58 minutes, with a maximum time of 75 minutes and a minimum time of 45 minutes.

Concrete properties were consistent and generally met specifications throughout the deck, but pumping was a significant challenge for LC-HPC-5, particularly while pumping the 0.42 and 0.43 *w/c* ratio mixtures.

Qualification Batch (6/7/2007). The qualification batch was the same as for LC-HPC-4 described in Section 5.3.13.

Qualification Slab (9/14/2007). The qualification slab was the same as for LC-HPC-4 described in Section 5.3.13.

Deck Placement (11/14/2007). The placement of LC-HPC-5 occurred on November 14, 2007 with construction starting at approximately 3:00 a.m. The last burlap was placed at 11:00 a.m., for a total construction time of 8 hours. The average placement rate for the placement was approximately 40 m^3/hr (53 yd^3/hr). Air temperatures during the placement ranged from 12 to 13ºC (54 to 56ºF), with a minimum and maximum air temperature for the day of 4º and 19ºC (39º and 66ºF) according to weather station data. Air temperatures dropped below freezing on days 8 through 14 of the 14-day curing period, and below 4ºC (40ºF) on all but one of the days. As with the other bridges in this contract, the girders were wrapped, as shown in Fig. 5.34, and heat was provided during the curing period.

Concrete was tested with samples taken from the ready-mix trucks prior to placement on the deck. Lindquist et al. (2007) reported that the air loss through the pump was 0.6% for the first truck. In general, the concrete test results were very good and consistent throughout the placement. Test records indicate that the slump ranged from 50 to 100 mm (2.0 to 4.0 in.) with an average of 78 mm (3.1 in.). One truck had a high slump, 140 mm (5.5 in.), and was held for 10 minutes. When it was retested, the slump was 100 mm (4 in.) and the truckload was placed in the deck. Air contents ranged from 6.8% to 10.3%, with an average of 8.7%. Only one truck did not meet the specifications for air content at 10.3%. The concrete surface temperature ranged from 14º to 18ºC (57º to 64ºF) with an average of 16ºC (61ºF). The slump and air content for the first truck was high, so it was held for about 20 minutes and then retested. The truck then met specifications [slump = 70 mm (in.) and air content = 8.0%] and was placed in the deck. Trucks 2 and 3 met all the specifications. There were no delays in the concrete delivery throughout the placement, but at times trucks sat for more than 45 minutes due to concrete pumping difficulties, as described next.

Fig. 5.34 Girders wrapped and heated on LC-HPC-5

There were significant problems with concrete pumping during the placement of LC-HPC-5 particularly while pumping the 0.42 and 0.43 *w/c* ratio mixtures. The pump seized three separate times while pumping the first seven trucks, which had a *w/c* ratio of 0.42. These delays resulted in trucks waiting to be discharged for more than 45 minutes. In an effort to improve the pumpability and avoid additional delays, the concrete supplier, without notification or approval by KDOT or KU, began to secretly add water to the trucks on site. The contractor then notified KDOT of what they had done and were praised for their actions. Shortly after KU became aware of the situation and, at KU's request, the design *w/c* ratio was increased to 0.43 to provide a clear record of the mixtures used in the deck. The pumping did not appear to improve with the 0.43 *w/c* ratio mixture, and upon the recommendation of KU, the design *w/c* ratio was again increased to 0.45. At this higher *w/c* ratio, the concrete was pumpable and construction could progress, although the surface did not finish as smoothly as for other LC-HPC placements.

Placement in LC-HPC-5 was uphill from west to east, from the west abutment to Pier #4. The pump was positioned at the abutment level for the initial portion of the deck, then subsequentially moved to locations beside (below) the deck for later portions of the deck that were more elevated. An air cuff was used at the pump discharge to limit air loss. Consolidation was with the same gang vibrator system used on LC-HPC-6 and the other decks in this contract.

The concrete was finished using a single-drum roller screed and a bullfloat. There were some voids in the concrete surface, the largest ones being the in the second quarter of the placement during the pumping problems. Fogging was not used, and the evaporation rate was not recorded for this placement.

For LC-HPC-5, the method of burlap placement was different than for previous placements, with a critical change potentially effecting cracking on the deck. The burlap pieces were not long enough to reach all the way across the deck. Instead of placing two pieces of burlap across the deck, one piece was placed transversely starting from the northwest side of the deck toward the southeast (superelevated) side, leaving an exposed area of concrete along the southeast side of the deck, ranging from 0.3 to 0.9 m (1 to 3 ft) wide plus the area containing the barrier steel. The concrete along the superelevated edge was left exposed and unprotected for extended periods of time while four or five widths of burlap were placed transversely, covering the majority of the deck surface. After placing four or five pieces of burlap transversely, workers then returned to the exposed concrete strip and placed a piece of burlap longitudinally over the unprotected concrete. The entire deck width should be protected with wet burlap as soon as possible after finishing.

Crack surveys have shown that the superelevated southeast side of the LC-HPC-5 deck had relatively high amounts of cracking at 8 months of age. Gruman et al. (2009) attributed this unusual cracking to curing water draining away from the superelevated edge and to higher than normal slumps contributing to settlement cracking on the superelevated edge. Because the average slump for concrete placed in this deck was 78 mm (3.1 in.), similar to most of the other LC-HPC decks in this study and not unusually high, it is likely that the extended exposure of the concrete along the superelevated side during the delayed placement of the burlap was a prime contributor to the increase in cracking. Slightly higher cracking was found along the superelevated edge of LC-HPC-6 [average slump = 96 mm (3.8 in)]. Therefore, the lack of a soaker hose along the superelevated edge may have also been a contributor to the early age cracking, although it does not appear to have been directly documented. For LC-HPC-6, the higher slump may have also lead to increased settlement cracking.

In support of this theory, evaporation rates for the placement of LC-HPC-5 were estimated using weather station records at the Olathe Airport. These records indicate that the air temperature during the placement (3:00 a.m. to 11:00 a.m.) ranged from 9° to 12°C (48° to 53°F), with wind speeds ranging from 11 to 16 mph and relative humidity dropping from 59% at 3:00 a.m. to 27% by 11:00 a.m. For the average concrete temperature of 16°C (61°F) and an air temperature of 10°C (50°F,) these conditions would create evaporation rates ranging from 0.49 to 0.93 $kg/m^2/hr$

(0.10 to 0.19 lb/ft^2/hr). These values of evaporation rate are below but approach the level [1.0 kg/m^2/hr (0.20 lb/ft^2/hr)] where measures should be taken to protect concrete from evaporation because of the risk for plastic shrinkage cracking.

The burlap placement was somewhat slow for LC-HPC-5. Delays due to pumping occurred throughout the placement, even after the mix design was changed to a *w/c* ratio of 0.45, but none of the pumping difficulites created a significant delay in the burlap placement. The average time between finishing and burlap placement was 12 minutes, with a minimum time of 5 minutes and a maximum time of 22 minutes. Twenty five of 33 (76%) locations timed exceeded the 10 minute requirement, with times ranging from 11 to 22 minutes and two stations exceeding 15 minutes. The in-place burlap was kept wet by using hoses to spray the burlap. During the last third of the placement, the burlap pieces were damp but not saturated when they were placed on the deck. The damp pieces of burlap were then sprayed, generally within 2 minutes, after placement on the deck. Soaker hoses were placed on about 2/3 of the deck by the time the placement was completed.

The average haul time from loading to discharge was 58 minutes, with an minimum time of 45 minutes and a maximum time of 75 minutes.

No form removal dates were obtained for LC-HPC-5.

Response from Personnel and Post-Construction Conference (5/28/2008). The post-construction conference for LC-HPC-3, 4, 5, and 6 occurred on May 28, 2008. Representatives from KDOT, the contractor, the concrete supplier, and KU were participated and provided feedback covering all of the bridges.

The contractor said he thought LC-HPC was a good product once it is completed, and that it can be completed well as we saw on the I-635 bridges (LC-HPC-1 and 2). The placement of the four bridges in this project was very difficult, which surprised the contractor because of the good first experience on the I-635 bridges. The concrete did not pump well and was very hard to finish when it was too dry. If the concrete can be pumped, then the price is about right, but if multiple placements are required, then the price will increase by about 25% in his estimation.

There is very little latitude in the specifications for inevitable variability in the field for gradations, *w/c* ratio, and temperatures. The contractor also indicated that the temperature specifications are very tight and that it cost about $100,000 USD to heat the bridges. He indicated that heating the decks and girders costs about 20-25% more and that scheduling and temperatures will be taken into account in future bids. The contractor felt that they could perform the finishing, covering, and fogging specifications adequately. The contractor indicated that they do not like the overlay decks.

The concrete supplier reported that the changes in the mix design between the I-635 bridges and the I-435 bridges consisted of a decrease in the *w/c* ratio from 0.45 to 0.42, using a high-range water reducer instead of a mid-range water reducer, and using an angular manufactured sand instead of a rounded pea gravel natural sand. He indicated that on paper, the gradations changed over time and that the manufactured sand was the perfect filler for the gradations. Fordyce had a petrographic analysis of the concretes done to check the *w/c* ratio of the in-place concrete. He reported that the results showed *w/c* ratios of 0.42 to 0.46. He indicated that higher strengths are obtained when using a high-range water reducer instead of a mid-range water reducer.

KDOT indicated that they would like to have some way to predict whether a mix design was pumpable.

KU indicated that based on these experiences, manufactured sand is not recommended and the strengths for these bridges was high. For the next bridges it was recommended that the same methods and equipment should be used on the qualification slab and deck. The temperature of the girders was not controlled during heating.

Lessons Learned. The contractor and concrete supplier changed the mixture without communication or approval from KDOT or KU. They also added water to the trucks without informing KDOT or KU. KU learned of the changed part way through the placement and worked with the contractor and supplier to establish a concrete mixture that was suitable for placement.

Cracking along the superelevated edge of LC-HPC-5 corresponds with delayed placement of burlap, where areas of the finished concrete were left exposed for extended periods, which increases the risk for plastic shrinkage cracking. These areas also may have had little or no water during the curing period because it is not clear that a soaker hose was placed along the superelevated edge of the deck. LC-HPC-6 exibited similar cracking along the superelevated edge of the deck, but had higher average slump and no reported delay in curing in these locations.

If girders are heated, positive temperature control should be established to keep temperatures within the required range.

Pumping the concrete and temperature control can effect the price of the bridge by 25%.

Manufactured sand is not recommended for use in LC-HPC.

Air cuffs reduce the amount of air loss and keep the system charged.

5.3.17 Control Bridge 3

Control 3 is part of the major I-435 contract in Kansas City, as discussed in Section 5.3.13. It is the companion structure to LC-HPC-3, the westbound bridge at the same location.

The Control 3 bridge deck was completed on July 17, 2007. Dates related to the construction of Control 3 are shown in Table 5.17.

Table 5.17 – Construction Dates for Control 3

Item Constructed	Date Completed
Subdeck Placement	7/6/2007
Silica Fume Overlay (SFO) Placement	7/17/2007

Design. Control 3 is the eastbound bridge on 103rd Street over US-69. It is a four-span, steel plate-girder bridge with non-integral end conditions, a 6 degree skew, and solid corral rail barriers separating the south edge of the deck as a sidewalk.

Control 3 is 115.91 m (380.3 ft) long. The four span lengths are 22.2 m (72.9 ft), 35.3 m (115.8 ft), 35.3 m (115.8 ft), and 22.2 m (72.9 ft). The total width of Control 3 is 16.41 m (53.8 ft).

The top mat of reinforcing steel in the deck of Control 3 consists of No. 16 (No. 5) bars spaced at 160 mm (6.3 in.). The deck is designed to have 75 mm (3.0 in.) of top cover and 30 mm (1.2 in.) of bottom cover. The subdeck depth is 180 mm (7.1 in.) and the SFO depth is 40 mm (1.6 in.), for a total depth of 220 mm (8.7 in.).

Concrete. The concrete mix designs for both the subdeck and the SFO meet the KDOT specifications for this type of structure. The concrete mix for the Control 3 subdeck, and all other subdecks in this contract, was not the standard KDOT mix. It contained 318 kg/m^3 (535 lb/yd^3) of Type I/II cement and 79 kg/m^3 (133 lb/yd^3) of fly ash, for a total cementitious material content of 397 kg/m^3 (668 lb/yd^3), providing a paste content of 29.0% by volume.

For these subdecks, the *w/cm* ratio was 0.40, and the design air content was 6.5%. The aggregate used in the subdecks was a 50:50 blend of natural sand (BSG_{SSD} = 2.61) and granite (BSG_{SSD} = 2.63) from Arkansas. The silica fume overlay concrete included a 7% silica fume replacement of cement, or 26 kg/m^3 (44 lb/yd^3), a *w/cm* ratio of 0.37, and an air content of 6.5%. Granite (BSG_{SSD} = 2.63) from Arkansas was used as the coarse aggregate.

Deck Placement. The deck placements were not observed for Control 3 and standard practices are assumed to have been used, including a 7-day curing period.

Construction occurred in two placements. The subdeck was placed on July 6, 2007. Concrete test records indicate that for the subdeck, the average slump was 169 mm (6.7 in.) and the average air content was 5.8%. The SFO was placed on July 17, 2007. Concrete test records indicate that for the SFO, the average slump was 185 mm (7.3 in.) and the average air content was 6.7%.

KDOT records indicate that the average evaporation rate was 0.14 kg/m^2/hr (0.028 lb/ft^2/hr) during the subdeck placement and 0.20 kg/m^2/hr (0.04 lb/ft^2/hr) during the SFO placement, both below the maximum limit of 1.0 kg/m^2/hr (0.2

lb/ft^2/hr), and therefore no measures to reduce the evaporation rate were required. Weather station data indicates that the daily high/low air temperatures for the two placements were 21º / 32ºC (70º / 90ºF) on July 6, 2007, and 22º / 33ºC (72º / 91ºF) on July 17, 2007.

Minor scaling was documented on Control 3 during a crack survey in 2008.

5.3.18 Control Bridge 4

Control 4 is part of the major I-435 contract in Kansas City, as discussed previously in Section 5.3.13.

The Control 4 bridge deck was completed on November 16, 2007. Dates related to the construction of Control 4 are shown in Table 5.18.

Table 5.18 – Construction Dates for Control 4

Item Constructed	Date Completed
Subdeck Placement	10/20/2007
Silica Fume Overlay (SFO) Placement	11/16/2007

Design. The Control 4 bridge is the Antioch Road to westbound I-435 ramp. It spans over the 103rd Street to US-69 south ramp. It is a five-span, steel plate-girder bridge with non-integral end conditions, no skew, and jersey barriers.

Control 4 is 213.8 m (701.5 ft) long. The five span lengths, from west to east, are 40.8 m (133.9 ft), 51.0 m (167.3 ft), 51.0 m (167.3 ft), 40.0 m (131.2 ft), and 30.3 m (99.4 ft). The total width of Control 4 is 12.43 m (40.78 ft).

The top mat of reinforcing steel in the deck of Control 4 consists of No. 19 (No. 4) bars spaced at 250 mm (9.8 in.). The deck is designed to have 75 mm (3.0 in.) of top cover and 30 mm (1.2 in.) of bottom cover. The subdeck depth is 180 mm (7.1 in.) and the SFO depth is 40 mm (1.6 in.), for a total depth of 220 mm (8.7 in.).

Concrete. The concrete mix designs for both the subdeck and the SFO meet the KDOT specifications for this type of structure and are as described for Control 3 in Section 5.3.17.

Deck Placement. Construction occurred in two placements. The subdeck was placed on October 20, 2007. Concrete test records indicate that for the subdeck, the average slump was 195 mm (7.7 in.) and the average air content was 7.3%. The SFO was placed on November 16, 2007. Concrete test records indicate that for the SFO, the average slump was 147 mm (5.8 in.) and the average air content was 6.9%.

The subdeck placement on October 20, 2007 was observed by KU personnel. Concrete testing was performed on the deck on samples taken after the pump. There did not appear to be channels of communication with the concrete supply regarding the results of the testing.

An air air cuff was not attached at the discharge end of the pump discharge to limit air loss.

The concrete was finished with a double-drum roller screed followed by a bullfloat. The very high slumps made concrete extremely easy to finish. However, to ease the finishing more, the workers sprayed the surface of the concrete with water after the screed and prior to bullfloating. The surface of the concrete at the screed appeared to have layers of paste floating on top of the concrete.

In accordance with standard KDOT practice, the subdeck was not fogged. Burlap placement occurred 15 to 23 m (50 to 75 ft) behind the finishing operations. The burlap placement crew indicated that for this bridge, they were placing the burlap much sooner than normal practice because they did not want to come back to place it after lunch. Burlap was lifted to the work bridges on pallets with a crane and placed longitudinally on the deck. The burlap appeared to be prewet. The burlap was not overlapped sufficiently, so pieces of burlap were dislocated by the wind, exposing sections of the deck surface, as shown in Fig. 5.35. Two soaker hoses were placed longitudinally along the deck on top of the burlap to keep it wet.

Fig. 5.35 Burlap that was not overlapped sufficiently, so pieces were dislocated by the wind leaving concrete exposed

There were fewer workers than for most LC-HPC placements, and the pace of work appeared to be more relaxed for placement before the screed, finishing, and burlap placement, as well as for the KDOT testing crew.

Standard curing periods of 7 days are assumed.

KDOT records indicate that the average evaporation rate during the subdeck placement was 0.26 kg/m^2/hr (0.053 lb/ft^2/hr), below the maximum limit of 1.0 kg/m^2/hr (0.2 lb/ft^2/hr), and no measures to reduce the evaporation rate were required. Evaporation rate conditions were not recorded for the SFO placement. Weather station data indicates that the daily high/low air temperatures for the two placements were 10º / 19ºC (50º / 67ºF) on October 20, 2007, and 1º / 11ºC (33º / 51ºF) on November 16, 2007.

5.3.19 Control Bridge 6

Control 6 is part of the major I-435 contract in Kansas City, as discussed in Section 5.3.13.

The Control 6 bridge deck was constructed in a total of seven placements with the last placement completed on October 20, 2008. Dates related to the construction of Control 6 are shown in Table 5.19.

Table 5.19 – Construction Dates for Control 6

Item Constructed	Date Completed
Subdeck - Placement 1 (seq. 1 & 2)	9/16/2008
Subdeck – Placement 2 (seq. 3)	9/18/2008
Subdeck – Placement 3 (seq. 5 & 6)	9/23/2008
Subdeck – Placement 4 (seq. 4)	9/26/2008
Subdeck – Placement 5 (seq. 7)	9/30/2008
Silica Fume Overlay (SFO) – Placement 1	10/16/2008
Silica Fume Overlay (SFO) – Placement 2	10/20/2008

Design. The Control 6 bridge is the fourth unit of the south bound US-69 to eastbound I-435 ramp. This portion of the flyover spans from Pier #10 (including Piers #11, 12, and 13) to the east abutment. It is a four-span, curved steel plate-girder bridge with one non-integral end condition (at Pier #10) and one integral end condition (at the east abutment), and jersey barriers. The third unit of this bridge is Control 5, another control deck in this study.

Control 6 is 268.9 m (882.2 ft) long. The four span lengths, from west to east, are 64.9 m (212.8 ft), 73.0 m (239.5 ft), 73.0 m (239.5 ft), and 58.0 m (190.3 ft). The total width of Control 6 is 12.43 m (40.78 ft).

The top mat of reinforcing steel in the deck of Control 6 consists of No. 19 (No. 6) bars spaced at 180 mm (7.1 in.). The deck is designed to have 75 mm (3.0 in.) of top cover and 30 mm (1.2 in.) of bottom cover. The subdeck depth is 190 mm (7.1 in.) and the SFO depth is 40 mm (1.6 in.), for a total depth of 230 mm (9.1 in.). Control 5 and 6 are the thickest decks in this study.

Concrete. The concrete mix designs for both the subdeck and the SFO meet the KDOT specifications for this type of structure and are as described for Control 3 in Section 5.3.17.

Deck Placement. The deck placements were not observed for Control 6 and standard practices are assumed to have been used, including a 7-day curing period.

Construction occurred in seven placements, five subdeck placements and two silica fume overlay placements. The subdeck was placed in a casting sequence, described in Appendix D, that was somewhat modified from that in the bridge plans.

The first subdeck placement (on September 16, 2008) included sequence sections 1 and 2. Concrete records indicate that the average slump was 206 mm (8.1 in) and the average air content was 7.4%.

The second placement (on September 18, 2008) included sequence section 3. The concrete test records are not available for this placement.

The third placement (on September 23, 2008) included sequence section 5 and 6). Concrete test records indicate that the average slump was 173 mm (7.3 in) and the average air content was 6.4%.

The fourth placement (on September 26, 2008) included sequence section 4. Concrete test records indicate that the average slump was 158 mm (6.2 in) and the average air content was 6.6%.

The fifth placement (on September 30, 2008) included sequence section 5 of the subdeck. The concrete test records are not available for this placement.

The west 2/3 of the SFO placed on October 16, 2008 and the east 1/3 placed on October 20, 2008. Concrete test records for the first SFO placement indicate that the average slump was 175 mm (7.0 in.) and the average air content was 7.7%. The results for the second SFO placement indicate that the average slump was 210 mm (8.4 in.) and the average air content was 8.1%.

KDOT records indicate that the average evaporation rate was 0.17 kg/m^2/hr (0.035 lb/ft^2/hr) during the first subdeck placement, 0.26 kg/m^2/hr (0.054 lb/ft^2/hr) during the third subdeck placement, and 0.27 kg/m^2/hr (0.056 lb/ft^2/hr) during the fourth subdeck placement. Records for the second and fifth subdeck placement were not obtained. The KDOT records for the average evaporation rate for the two SFO placements were 0.28 kg/m^2/hr (0.057 lb/ft^2/hr) and 0.23 kg/m^2/hr (0.047 lb/ft^2/hr), respectively. All of the recorded evaporation rates are below the maximum limit of 1.0 kg/m^2/hr (0.2 lb/ft^2/hr), and therefore no measures to reduce the evaporation rate were required. Weather station data indicates that the daily high/low air temperatures for the seven placements were 8º / 23ºC (47º / 73ºF) on September 16, 2008, 13º / 27ºC (55º / 80ºF) on September 18, 2008, 16º / 26ºC (61º / 79ºF) on September 23, 2008, 15º / 28ºC (59º / 82ºF) on September 26, 2008, 9º / 23ºC (49º / 73ºF) on September 30, 2008, 3º / 13ºC (38º / 55ºF) on October 16, 2008, and 9º / 22ºC (49º / 72ºF) on October 20, 2008.

5.3.20 Control Bridge 5

Control 5 is part of the major I-435 contract in Kansas City, as discussed previously in Section 5.3.13.

The Control 5 bridge deck was constructed in a total of five placements with the last placement completed on November 25, 2008. Dates related to the construction of Control 5 are shown in Table 5.20.

Table 5.20 – Construction Dates for Control 5

Item Constructed	Date Completed
Subdeck - Placement 1 (seq. 1 & 2)	11/8/2008
Subdeck – Placement 2 (seq. 3, 5, and 6)	11/13/2008
Subdeck – Placement 3 (seq. 4 & 7)	11/17/2008
Silica Fume Overlay (SFO) – Placement 1 (west half)	11/22/2008
Silica Fume Overlay (SFO) – Placement 2 (east half)	11/25/2008

Design. The Control 5 bridge is the third unit of the south bound US-69 to eastbound I-435 ramp. This portion of the flyover spans from Pier #6a (including

Piers #7, 8, and 9) to Pier #10. It is a four-span, curved steel plate-girder bridge with non-integral end condition, and jersey barriers. The fourth unit of the bridge serves as Control 6 in this study.

Control 5 is 250.6 m (822.2 ft) long. The four span lengths, from west to east, are 45.6 m (149.6 ft), 71.0 m (232.9 ft), 71.0 m (232.9 ft), and 63.0 m (206.7 ft). The total width of Control 5 is 12.43 m (40.78 ft).

The top mat of reinforcing steel in the deck of Control 5 consists of No. 19 (No. 6) bars spaced at 180 mm (7.1 in.). The deck is designed to have 75 mm (3.0 in.) of top cover and 30 mm (1.2 in.) of bottom cover. The subdeck depth is 190 mm (7.1 in.) and the SFO depth is 40 mm (1.6 in.), for a total depth of 230 mm (9.1 in.). Control 5 and 6 are the thickest decks in this study.

Concrete. The concrete mix designs for both the subdeck and the SFO meet the KDOT specifications for this type of structure and was as described for Control 3 in Section 5.3.17.

Deck Placement. The deck placements were not observed for Control 5 and standard practices are assumed to have been used, including a 7-day curing period.

Construction occurred in five placements, three subdeck placements and two silica fume overlay placements. The subdeck was placed in a casting sequence that was somewhat modified from that in the bridge plans. The casting sequence is provided in Appendix D.

The first subdeck placement (on November 8, 2008) included sequence sections 1 and 2. Concrete records indicate that the average slump was 200 mm (8.0 in) and average air content was 5.6%.

The second placement (on November 13, 2008) included sequence sections 3, 5, and 6. Concrete records indicate that the average slump was 232 mm (9.1 in) and average air content was 6.8%.

The third placement (on November 17, 2008) included sequence sections 4 and 7. Concrete test records indicate that the average slump was 206 mm (8.1 in) and the average air content was 5.4%.

The west half of the SFO placed on November 22, 2008 and the east half placed on November 25, 2008. Concrete test records for the first SFO placement indicate that the average slump was 150 mm (6.0 in.) and the average air content was 7.6%. The results for the second SFO placement indicate that the average slump was 230 mm (9.1 in.) and the average air content was 6.6%.

KDOT records indicate that the average evaporation rate was 0.23 kg/m^2/hr (0.048 lb/ft^2/hr) during the first subdeck placement, 0.43 kg/m^2/hr (0.088 lb/ft^2/hr) during the second subdeck placement, and 0.37 kg/m^2/hr (0.076 lb/ft^2/hr) during the third subdeck placement. The KDOT records for the average evaporation rate for the two SFO placements were 0.23 kg/m^2/hr (0.048 lb/ft^2/hr) and 0.27 kg/m^2/hr (0.056 lb/ft^2/hr), respectively. All of the recorded evaporation rates are below the maximum limit of 1.0 kg/m^2/hr (0.2 lb/ft^2/hr), and therefore no measures to reduce the evaporation rate were required. Weather station data indicates that the daily high/low air temperatures for the seven placements were 0º / 7ºC (32º / 44ºF) on November 8, 2008, 6º / 11ºC (42º / 51ºF) on November 13, 2008, 1º / 14ºC (33º / 58ºF) on November 17, 2008, –9º / 2ºC (16º / 36ºF) on November 22, 2008, and –2º / 11ºC (29º / 51ºF) on November 25, 2008.

5.3.21 LC-HPC Bridge 12

The twelfth LC-HPC bridge deck let in Kansas (LC-HPC-12) is the second unit of the bridge located on K-130 over the Neosho River near Hartford, KS and southeast of Emporia. The contract contained one bridge and was awarded to A. M. Cohron Construction. Control 12 is the first unit of this bridge. Both LC-HPC-12 and Control 12 were constructed in two phases. LC-HPC-12 was the thirteenth LC-HPC bridge deck completed in Kansas. The bridge decks for the first and second phases of LC-HPC-12 were completed on April 4, 2008 and March 18, 2009, respectively. Dates related to the construction of LC-HPC-12 are shown in Table 5.21.

Table 5.21 – Construction Dates for LC-HPC-12

Item Constructed	Date Completed
Qualification Batch - Phase 1	3/25/2008
Qualification Slab - Phase 1	3/28/2008
LC-HPC Deck - Phase 1 (east)	4/4/2008
Qualification Batch - Phase 2	3/12/2009
Qualification Slab - Phase 2	None
LC-HPC Deck - Phase 2 (west)	3/18/2009
Post-Construction Meeting	Not yet scheduled

Design. The K-130 over the Neosho River Bridge, sometimes referred to as the Hartford bridge, is a six-span, steel plate-girder bridge with integral abutments, corral rails, and no skew. The bridge is divided into two units, each with three spans, separated by an expansion joint. Control 12 is Unit 1, including the southern three spans (Abutment #1 to Pier #3), and LC-HPC-12 is Unit 2, including the northern 3 spans (Pier #3 to Abutment #2). The phases for both units (Control 12 and LC-HPC-12) consisted of approximately half of the final bridge width.

The whole bridge, LC-HPC-12 and Control 12 together, is 254.0 m (833.0 ft) long, with LC-HPC-12 and Control 12 each being 127.0 m (416.5 ft) long. The three span lengths for LC-HPC-12, from the north abutment (Abutment #2) to Pier #3 (the center construction joint for the whole structure) are 39.6 m (130.0 ft), 43.4 m (142.5 m) and 43.0 m (141.0 ft).

The total width of the Hartford bridge is 11.6 m (38 ft). For each unit, Phase 1 (east side), was constructed in one 5.49 m (18.0 ft) wide placement, while Phase 2 (west side), was constructed in one 6.10 m (20.0 ft) placement.

The LC-HPC-12 deck is monolithic with a total depth of 216 mm (8½ in.), 75 mm (3 in.) of top cover, and 38 mm (1½ in.) of bottom cover. The top mat of reinforcing steel consists of No. 16 (No. 5) bars spaced at 150 mm (6 in.).

Concrete. Builder's Choice Concrete in Emporia, a subsidiary of Concrete Supply of Topeka (CST), provided the concrete for the LC-HPC-12 deck, with a haul distance of 31 km (19 mi) and a haul time of approximately 45 minutes. For Phase 1 of LC-HPC-12, the average time from loading to discharge was 57 minutes, with a maximum time (at the beginning of the placement) of 81 minutes and a minimum time of 43 minutes.

The specifications for LC-HPC-12 require a maximum cement content of 317 kg/m^3 (535 lb/yd^3) and a *w/c* ratio of 0.42. For previously constructed bridges, mixtures meeting these specifications had, at times, been difficult to place and finish compared to mixtures containing 320 kg/m^3 (540 lb/yd^3) and a *w/c* ratio of 0.45. So, for this deck the cement content and *w/c* ratio were increased. The concrete mix for Phase 1 of LC-HPC-12 had a cement content of 320 kg/m^3 (540 lb/yd^3) and a *w/c* ratio of 0.44, while the approved mix for Phase 2 had a cement content of 318 kg/m^3 (535 lb/yd^3) and a *w/c* ratio of 0.45. The design air content was 8.0%. The mixture contained three aggregates, including two granite coarse aggregates (BSG_{SSD} = 2.64) from Arkansas and one natural river sand fine aggregate (BSG_{SSD} = 2.63).

Qualification Batch – Phase 1 (3/25/2008). The qualification batch for Phase 1 was produced on March 25, 2008 in Emporia, Kansas with KU personnel on site. The concrete contained 320 kg/m^3 (540 lb/yd^3) of cement and had a *w/c* ratio of 0.45. Immediately after mixing, the concrete air content was 10.5%, the slump was 115 mm (4.5 in.), and the concrete temperature was 17°C (63°F). After the haul time was simulated, the air content had dropped to 8.0%, the slump was 100 mm (4.0 in.), and the concrete temperature was 18°C (65°F), meeting all specifications. Air temperatures in Emporia on the day of the qualification batch ranged from –1° to 16°C (30° to 61°F).

Qualification Slab (3/28/2008). The qualification slab for Phase 1 was placed on March 28, 2008, with placement beginning at approximately 9:15 a.m. The placement was completed in 4.5 hours. The air temperatures during placement were low, ranging from 3° to 4°C (38° to 39°F), and for the day from 2° to 8°C (36° to 47°F).

A 45-minute simulated haul time was observed for each of the trucks. The first truckload of concrete did not initially meet the specifications for slump [108 mm (4.25 in.)], so the truck was retested after 13 minutes and accepted with a slump of 95 mm (3.75 in.). The second truck also did not meet the specifications for slump [133 mm (5.25 in.)] even after waiting and retesting [114 mm (4.5 in.)]. However, the truck was eventually placed to avoid delaying the placement. The third truck was rejected with a 150-mm (6-in.) slump. The fourth and fifth trucks met the requirements for slump. The average slump of the concrete placed in the qualification slab was 94 mm (3.7 in.). The average air content was 7.9% with a minimum of 7.5% and a maximum of 8.5%. The concrete temperature ranged from 13º to 15ºC (56º to 59ºF) with an average of 14ºC (57ºF).

Concrete was placed in the 5.5-m (18-ft) wide qualification slab with two buckets with capacities of 0.57 and 0.76 m^3 (0.75 and 1 yd^3). Buckets were used instead of a pump because at the bridge site the flooding river made soil conditions beside the bridge inadequate for a pump truck. Placement operations with the buckets went smoothly and more efficiently than expected. The average time to unload a truckload of concrete was 8.5 minutes. Loading and unloading the buckets was quick, and most of the time to unload a truck was used in swinging the buckets to the qualification slab. It was estimated that the average placement rate could be between 23 to 31 m^3/hr (30 to 40 yd^3/hr). Delays during placement of the qualification slab occurred due to a delay in the concrete supply. Because trucks were batched only after the previous load was accepted, the 45-minute simulated haul time resulted in a total time for the placement of approximately 4.5 hours, for just five truckloads of concrete, one of which was rejected.

The concrete finished well with a single-drum roller screed and a burlap drag attached to the screed. For the deck placements, a pan drag was used instead of a fabric drag. Bullfloating was not used for the qualification slab. The fogging equipment was mounted on the back side of the finishing bridge. The system consisted of solid pipe connecting 5 spray nozzles (Fig. 5.36). The fogging equipment was checked, but not used during the placement of the qualification slab. Rail reinforcement was not present or simulated in the qualification slab.

Fig. 5.36 Fogging system with solid pipe - did not deposit excessive water on the deck surface

Behind the finishing bridge, one work bridge was used to roll out the wet burlap (Fig. 5.37a). The burlap was placed by hand from the sides of the deck (Fig. 5.37b) in front of the bridge and up toward the finishing equipment. At times, the burlap was placed within 0.3 to 0.6 m (1 to 2 ft) of the finishing equipment. The average burlap placement time was 5.3 minutes, with a maximum time of 10 minutes during start-up and a minimum time of 3 minutes at two different locations along the slab. Delays in the burlap placement corresponded with a delay in the concrete supply from approximately 9:50 a.m. to 11:00 a.m.

(a) Burlap rolled out onto the work bridge

(b) Burlap placed from the sides of the deck

Fig. 5.37 Efficient burlap placement for a narrow bridge deck placement

Deck Placement Phase 1 - East (4/4/2008). The first placement (Phase 1) for LC-HPC-12 occurred on April 4, 2008, with construction starting at approximately 8:45 a.m. The last burlap was placed at 4:56 p.m., for a total time of 5.7 hours. The average placement rate was approximately 30 m^3/hr (39 yd^3/hr). Air temperatures during the placement ranged from 7 to 17ºC (44 to 63ºF), with minimum and maximum air temperatures of 3º and 9ºC (37º and 48ºF) according to the National Oceanic and Atmospheric Administration (NOAA) "Emporia NW" weather station. This illustrates the fact that on-site environmental conditions can vary from the conditions recorded by weather stations. Air temperatures dropped below freezing on days 5, 9, and 10 of the 14-day curing period, and below 4ºC (40ºF) on 10 of the 14 days. The bridge was not heated, and the additional curing above 10ºC (50ºF) was insufficient as described in detail later in this section.

The KDOT concrete test records indicate that the slump ranged from 45 to 90 mm (1.75 to 3.5 in.) with an average of 70 mm (2.75 in.). Air contents ranged from 6.2% to 8.1%, with an average of 7.4%. The concrete temperature ranged from 12 to 16ºC (53 to 60ºF) with an average of 14ºC (57ºF). The first two trucks were adjusted at the site, the first by adding water that had be withheld into the mix to increase the *w/c* ratio from 0.42 to 0.44 and the second truck using a mid-range water reducer. The first truckload had low air (6.2%) but was accepted because it was placed in the abutment. The second truckload had a low slump of 45 mm (1.75 in.), which was within specifications. Testing was performed on concrete sampled after it was deposited on the deck by the bucket. There were no delays in the concrete delivery during the day.

The placement of Phase 1 of LC-HPC-12 went very smoothly. The concrete was placed using two buckets, which were loaded from concrete trucks located on the remaining portion of the deck of the existing (old) structure and lifted over the temporary traffic barrier with a crane, located on the existing structure. Placement was from north to south, from Abutment #2 to Pier #3. The concrete was finished using a single-drum roller screed and a pan drag attached to the screed. Floating was performed only at the beginning and the ends of the deck at locations where the pan drag could not reach. Fogging was not used, and the maximum evaporation rate for the placement was 0.24 kg/m^2/hr (0.05 lb/ft^2/hr).

Rolls of presoaked burlap were pre-positioned along the deck and unrolled across a work bridge following the finishing bridge. The burlap was lifted from the sides of the deck and efficiently placed at distances of approximately 1.2 m (4 ft) behind the finishing equipment for most of the deck. The average time between finishing and burlap placement was 7 minutes, with a minimum time of 4 minutes and a maximum time of 12 minutes. Three of 22 (14%) locations timed exceeded the 10 minute requirement, with times of 11, 12 and 12 minutes. Two layers of burlap were placed at the same time. The in-place burlap was kept wet by using hoses to spray the burlap several times during the placement.

The average haul time from loading to discharge was 57 minutes, with an minimum time of 43 minutes and a maximum time of 81 minutes.

The cold-weather curing provisions in the construction specification for LC-HPC-12 include requirements for enclosing and heating the deck and girders if the air temperature drops below 4ºC (40ºF) during the curing period. Previous experience with these requirements indicated difficulty in ensuring uniform and consistent temperature during heating. As discussed next, current specifications provide an alternate option, allowing heating to be stopped after the first 72 hours of the curing period if the curing time is increased to account for periods during the original 14-day curing period when the air temperature is below 4ºC (40ºF). For every day that the ambient air temperature is below 4ºC (40ºF), an additional day of curing with a minimum ambient air temperature of 10ºC (50ºF) is required. An hourly accounting for periods below 4ºC (40ºF) and above 10ºC (50ºF) is also acceptable but may require significant record keeping. Though these new specifications were not required for LC-HPC-12, they were allowed and followed by the contractor, but not fully. LC-HPC-12 is the first bridge for which the lengthened curing period was implemented.

The initial 14-day curing period was completed on April 18, 2008. However, the curing period was extended to account for periods the air temperature dropped below 40F. The wet curing was stopped on April 21, 2008, and a fugitive dye curing compound was applied after the removal of burlap. As noted previously, according to weather station data, air temperatures dropped to or below freezing on days 5, 9, and 10 (4/9/08, 4/13/08, and 4/14/08) during the initial 14-day curing period (4/4/2008-4/18/2009), and below 4ºC (40ºF) on 10 of the 14 days. As a result, a minimum of 81 hours of curing with temperature of 10ºC (50ºF) or greater should have been provided. This requirement was not met. Three additional days of curing were provided (4/19/08-4/21/09) totaling 47 hours of curing above 10ºC (50ºF), rather than the required 81. No records of the determination of the extended curing period were made; therefore, weather data was taken from Emporia airport weather station. In summary, the required extension of curing due to low temperatures during the standard curing period was not managed and the additional curing period was insufficient.

The forms were removed from LC-HPC-12 and Control 12 Phase 1 starting on 5/19/2008 and finished by 5/23/2008, 45 to 49 days after the Phase 1 LC-HPC-12 deck was cast.

The corral rail for LC-HPC-12 Phase 1 was cast on May 2, 2008. The average air content was 7.4%, the average slump was 79 mm (3.1 in.), and the average concrete temperature was 21°C (69°F). The air temperature during corral rail casting was 13°C (55°F).

Qualification Batch – Phase 2 (3/12/2009). The Phase 2 qualification batch was performed on March 12, 2009 in Emporia, Kansas with KU personnel on site. The batch met the specifications for air content (7.0%), slump [95 mm (3.75 in.)], and concrete temperature [16°C (61°F)]. A haul time of 25 minutes was simulated prior to testing. The air temperature in Emporia during the qualification batch was approximately –2°C (28°F).

Deck Placement Phase 2 - West (3/18/2009). The second placement for LC-HPC-12 occurred on March 18, 2009, with construction starting at approximately 10:00 a.m. and ending at approximately 8:15 p.m. Measured air temperatures during the placement ranged from 11º to 15ºC (52º to 65ºF). Two mix designs were used, with *w/c* ratios of 0.45 and 0.44. At one point during the day, the evaporation rate exceeded 1.0 $kg/m^2/hr$ (0.2 $lb/ft^2/hr$) and measures, described in detail later, were taken to reduce the evaporation rate.

In general, the concrete supplier had difficulty controlling the concrete slump and air content throughout the placement. All of the concrete in the deck had a slump of 90 mm (3.5 in.) or higher. Concrete test results during the day indicated that the slump ranged from 90 to 140 mm (3.5 to 5.5 in.) with an average of 104 mm (4.1 in.). Five tested truckloads placed in the deck had a measured slump higher than 100 mm (4 in.). Air contents ranged from 6.3% to 9.0% with an average of 7.8%. One truckload placed in the deck had an air content of 6.3%, below the specified minimum of 6.5%. Several trucks with low air content were successfully redosed with air entraining agent to increase the air content to meet specifications. The concrete temperature ranged from 16º to 22ºC (61º to 72ºF) with an average of 19ºC (67ºF). Because the concrete properties were not consistent, additional testing was, at times, performed prior to placement in the deck. When test results were out of specification, the next load was generally checked before it was accepted for placement on the deck. In these cases, the concrete was sampled from the buckets, prior to placement on the deck. It is expected that the concrete properties did not vary significantly between discharge from the truck and placement with the bucket because the drop from the concrete bucket onto the deck was only approximately 1 m (3 ft). The concrete test results from the deck indicate that the concrete achieved a compressive strength of 28.8 MPa (4180 psi) for the 0.45 *w/c* ratio mixture and 31.6 MPa (4580 psi) for the 0.44 *w/c* ratio mixture.

The 0.45 *w/c* ratio mix had a high slump without any water reducer. When batching this mix, the supplier attempted to control the slump using heated water. For this mix, the mix water temperature (ratio of hot water to cold mix water) significantly affected the slump. By the eighth truck, the supplier was told to reduce the slump, and the concrete was switched to the 0.44 *w/c* ratio mixture, which achieved an acceptable slump. Without approval, the contractor requested the supplier to return to the 0.45 *w/c* ratio mix so that redosing with water reducer did not have to occur on site. Once this change was made, there was difficulty in meeting the specifications for slump and air content. The contractor then, needing to reduce the concrete temperature to control the increasing evaporation rate conditions [as high as 1.07 kg/m^2/hr (0.22 lb/ft^2/hr)], switched back to the 0.44 *w/c* ratio mixture and dropped the concrete temperature.

Concrete was placed with two buckets filled directly from the concrete trucks and lifted by a crane onto the deck. The direction of placement was from south to north (Pier #3 to Abutment #2). During the placement, the crane was located on the adjacent and connected Phase 1 deck. The concrete trucks backed up on the Phase 1 deck. Two alternating buckets were used to place the concrete. The concrete drop from the buckets to the deck was approximately 1 m (3 ft). The movement of the crane induced significant vertical movement (deflections) in the deck, particularly when swinging of the loaded boom while the crane was near mid-span. The vertical movement was quite noticeable (estimated visually to be up to 1½ in.), and there was concern whether the vertical movement of the connected decks would cause cracking in the very early age Phase 2 deck. Prior to placement of the Phase 2 deck, the contractor requested approval to discharge concrete trucks directly into the deck using extended chutes on the trucks. There was concern that due to the low slump, the LC-HPC concrete would not flow down long, nearly-horizontal chutes required to reach across the placement width of 16.1 m (20 ft) and the method was not adopted.

In general, the concrete was somewhat over-consolidated. For the first quarter of the deck, the vibration times ranged from 8 to 10 seconds. After the contractor was asked to reduce the time, the vibration times were closer to 5 to 6 seconds. Finishing operations went smoothly, and the deck surface finished well with a single-drum roller screed and a pan drag. The ends of the deck [approximately 2.4 m (8 ft)] were bullfloated. As instructed, the contractor never turned on the machine-mounted fogging system.

The burlap was stacked on pallets and covered with plastic, as if it had been presoaked but removed from water the day before. The top layers of burlap were dry, so the contractor was required to rewet the drying burlap prior to placement. When the inspectors were not watching, the crew placed the dry burlap. This caused some friction because they had to be instructed multiple times to not place dry burlap. The crew did not like carrying wet burlap that was dripping.

The burlap was rolled out on a work bridge and lifted onto the deck from the sides. Initially, they placed the burlap behind the work bridge, leaving a span of uncovered finished concrete under the work bridge and up to the finishing equipment. The contractor switched to placing the burlap in front of the finishing bridge when he was reminded that during Phase 1, they placed it in front of the work bridge and it cut down the time to covering the concrete. After he switched, the times decreased, and the crew had no trouble keeping up with the finishing, typically placing burlap within a couple feet of the finishing. The burlap placing times ranged from 1 to 24 minutes, with an average of 6.3 minutes. The time to burlap placement exceeded the 10-minute maximum at 5 of 41 stations (12%) timed along the deck, with times of 12, 18, 12, 13, and 24 minutes. The in-place burlap was kept wet periodically by spraying water with a hose.

In the final stages of the placement, the slumps for the final trucks was high, so each of the last three trucks was tested and only concrete that met specifications was placed in the deck. The concrete with high slump above 100 mm (4 in.) was placed in the abutment and the wing wall.

The contractor was significantly short on concrete and had to back-order 5.4 m^3 (7 yd^3), with a 45 to 60 minute delay. The contractor was told to place the concrete in the deck, finish the deck as much as possible, remove the finishing equipment and cover the whole deck, even the portions that were unfinished. One corner of the deck adjacent to the wing wall (north-west corner) with a radius of approximately 0.3 m (1 ft) was short on concrete and remained unfinished. When the concrete arrived, the contractor removed the burlap at the corner of the deck, finished the deck and then replaced the burlap.

The contractor was allowed to follow the new alternate provisions for extended curing during cold weather, in lieu of wrapping and heating the deck for the entire 14-day curing period. For Phase 2, the contractor was required to provide an hourly accounting for the extended curing. The air temperature dropped below 4ºC (40ºF) for 112 hours during the standard 14-day curing period (8:00 p.m. on 3/18/2009 to 8:00 p.m. on 4/1/2009). An additional 128 hours of curing above 10ºC (50ºF) were provided over 15 days, exceeding the required 112 hours. Burlap was removed from the LC-HPC-12 phase 2 deck on 4/16/2009 and forms were removed on days 56, 57, 64, 65, and 66 after the deck placement.

The surface temperature of the top girder flanges were measured and recorded throughout the day. The girder top flange surface temperature increased quickly after the sun rose and dropped quickly after the sun set. In general, the steel temperature was cooler than the air temperature during the early and late portions of the day, but was warmer than the air temperature from approximately 10:00 a.m. to 5:30 p.m.

For LC-HPC-12 Phase 2 construction, the KDOT manager was new, and a professor was not present during construction, but the senior author of this report was. Also, it was nearly a year between casting Phase 1 and Phase 2 LC-HPC decks, and a second qualification slab was not required between the phases of construction.

Average haul time from loading to discharge was 61 minutes.

Unique Considerations. Although not required for this bridge, alternate requirements for cold weather curing in the newest version of the specifications were implemented for LC-HPC-12 deck construction. Instead of wrapping the deck and heating the girders during the curing period, the new specification allows an alternative extension of curing beyond the standard 14 days to account for periods during the initial 14-day curing period when the air temperature drops below 4°C (40°F). The extended curing period consists of an hour of curing with air temperatures above 10°C (50°F) for every hour of curing when the air temperature drops below 4°C (40°F). The details of the requirements were discussed previously.

The Hartford Bridge, LC-HPC-12 and Control 12 together, consists of two units constructed in two phases over water. Unit 1 is the Control 12 structure, and Unit 2 is the LC-HPC-12 structure. Phases 1 and 2 were constructed in March 2008 and April 2009, respectively. A second qualification slab was not required for the Phase 2 LC-HPC construction, even though the construction of Phase 2 occurred nearly a year after Phase 1 construction. A second preconstruction conference was also not required, and most of the communication occurred through email, phone calls and at the qualification batch prior to construction of Phase 2. Some of the KDOT personnel involved in the project changed during the one year period between the completion of Phase 1 deck and before the beginning of Phase 2.

Difficulties occurred during the Phase 2 construction due to significant vertical deflections observed during construction. Specifically, portions of the Unit 1 Phase 2 (Control 12) subdeck were shallow, indicating potential problems for construction of the LC-HPC Phase 2 deck. Up to one day prior to construction of the Phase 2 LC-HPC deck, the contractor and KDOT were determining the method of placement of the LC-HPC concrete. KU recommended that the contractor demonstrate the placement method prior to placing the LC-HPC deck, and the contractor elected to place using the same method as used for Phase 1 while frequently checking the deck depth and adjusting the screed to maintain a consistent deck depth.

Personnel Response and Post-Construction Conference. A post-construction conference has not yet been scheduled.

Lessons Learned. Adding all of the water at the plant and adjusting the workability at the site with a mid-range water reducer worked well for Phase 1. After the first two truckloads of concrete, no adjustment was necessary. For Phase 2, while producing the 0.45 *w/c* ratio mixture that contained no water reducer, the supplier used heated water to control the slump. This strategy did not work well for controlling the slump and it also affected the air content.

The burlap was placed very efficiently with average times of 7.0 minutes for Phase 1 and 6.3 minutes for Phase 2.

Additional curing time required for air temperatures below 4ºC (40ºF) during the standard 14-day curing period must be actively managed and recorded. Not doing so resulted in insufficient curing for Phase 1.

With a year delay between placements, significant communication with the contractor and with KDOT personnel was required prior to the second placement to ensure that everyone remembered the new procedures.

5.3.22 Control Bridge 12

The Control 12 bridge deck is the first unit of the bridge located on K-130 over the Neosho River near Hartford, KS and southeast of Emporia. The contract contained one bridge and was awarded to A. M. Cohron Construction. LC-HPC-12 is the second unit of the bridge. Both LC-HPC-12 and Control 12 were constructed in two phases. The bridge deck for the first phase of Control 12 was completed on 4/1/2008 and the second phase was completed on 4/14/2009. Dates related to the construction of LC-HPC-12 are shown in Table 5.22.

Table 5.22 – Construction Dates for Control 12

Item Constructed	Date Completed
Subdeck Phase 1 (east)	3/11/2008
Silica Fume Overlay Phase 1 (east)	4/1/2008
Subdeck Phase 2 (west)	3/13/2009
Silica Fume Overlay Phase 2 (west)	4/14/2009

Design. The K-130 over the Neosho River Bridge, sometimes referred to as the Hartford bridge, is a six span, steel (plate) girder bridge with integral abutments, corral rails, and no skew. Details of the overall design are presented in Section 5.3.21.

The total width of Control 12 (and LC-HPC-12) is 11.6 m (38 ft). Phase 1, the east side, was constructed in one 5.49 m (18.0 ft) wide placement. Phase 2, the west side, is also being constructed in one 6.10 m (20.0 ft) placement.

The Control 12 deck is a silica fume overlay deck with a total depth of 216 mm (8½ in.), 75 mm (3 in.) of top cover, and 25 mm (1 in.) of bottom cover. The subdeck is 165 mm (6½ in.) and the silica fume overlay is 38 mm (1½ in.). The top mat of reinforcing steel consists of No. 16 (No. 5) bars spaced at 150 mm (6 in.).

Concrete. Builder's Choice Concrete, a subsidiary of Concrete Supply of Topeka (CST) provided the concrete for the Control 12 deck, with a haul distance of 31 km (19 mi) and a haul (placement) time of approximately 45 minutes.

The concrete mix designs for both the subdeck and the SFO meet the KDOT specifications for this type of structure. The concrete mix for the subdeck was the standard KDOT mix, containing 358 kg/m^3 (602 lb/yd^3) of Type I/II cement, a *w/c* ratio of 0.44, and a design air content of 6.5%. The aggregates used in the subdeck were a 50:50 blend of natural sand (BSG_{SSD} = 2.56) and limestone (BSG_{SSD} = 2.66). The mix design for the silica fume overlay concrete included a 7% silica fume replacement of cement, or 26 kg/m^3 (44 lb/yd^3), 345 kg/m^3 (581 lb/yd^3) of cement, a *w/cm* ratio of 0.37, and a design air content of 6.5%. Quartzite (BSG_{SSD} = 2.63) from South Dakota was used as the coarse aggregate in the overlay.

Deck placement. Construction occurred in two phases with two placements in each phase. The first phase included the east half of the deck and was constructed in March and April 2008. The second phase included the west half of the bridge and was constructed in March and April 2009. The deck placements were not observed, and standard practices are assumed to have been used, including a 7-day curing period. Relevant details for each placement obtained from the construction diaries are described next.

Subdeck – Phase 1 (3/11/2008). The subdeck for the east half of Control 12 was cast in mid-March with a recorded air temperature ranging from of 2° to 17°C (36° to 62°F). Placement started at approximately 9:00 a.m. and was completed by about 6 p.m. The concrete was placed with a pipe system, or "slick line," from north to south (Pier #3 to Abutment #1). The pump truck was located on the Abutment #1 approach and the concrete was pumped through the pipe line onto the bridge. The finishing equipment failed at approximately Pier 2 and was repaired within about 15 minutes. The concrete before and after the finishing equipment was covered with wet burlap while the equipment was repaired.

The test results for the subdeck placement on 3/11/2008 indicate an average air content of 6.9%, an average slump of 110 mm (4.3 in.), and an average concrete temperature of 23°C (74°F). The average haul time was 56 minutes from loading to discharge. The contractor placed the polyethylene sheeting on the burlap just before sunset. The forms were removed from Control 12 Phase 1 starting on 5/19/2008 and finished by 5/23/2009, 69 to 73 days after the Phase 1 subdeck was cast.

The deck was covered with blankets on days 3 and 4 of the curing period due to temperature forecast.

Silica Fume Overlay – Phase 1 (4/1/2008). The SFO for the east half of Control 12 was cast in early April with a recorded air temperature ranging from of 2° to 10°C (36° to 50°F). The construction diaries record that there were a lot of problems with the silica fume overlay concrete during the placement, particularly with the air content and delays. Some concrete was placed with a very low air content (2.5%) and some with a high air content (9.9%). Intermittent fogging was performed but this was stopped because the pre-cure compound was being washed off.

The test results for the SFO placement indicate an average air content of 6.8%, with a range from 2.5% to 9.9%. The average slump was 92 mm (3.6 in.), and the average concrete temperature was 15°C (59°F). The average haul time was 93 minutes from loading to discharge.

Subdeck – Phase 2 (3/13/2009). The subdeck was cast in mid-March with a recorded air temperature ranging from –1° to 8°C (30° to 46°F). Difficulties in achieving proper deck depth were encountered, producing a number of significant shallow depth areas. At times, the finishing equipment hit the reinforcing bars.

The test results for the subdeck placement on 3/13/2009 indicate an average air content of 7.2%, an average slump of 120 mm (4.7 in.) and an average concrete temperature of 22°C (72°F). The average haul time was 70 minutes from loading to discharge.

The forms were removed from Control 12 Phase 2 starting on 3/24/2009 and removal was completed by 4/10/2009, 28 days after the Phase 2 subdeck was cast, and prior to the SFO placement.

Silica Fume Overlay – Phase 2 (4/14/2009). The silica fume overlay for the west half of Control 12 was cast in mid-March. Weather station data indicate that minimum and maximum temperatures for the day ranged from 1° to 18°C (33° to 64°F).

The test results for the SFO placement on 4/14/2009 indicate an average air content of 7.7%, an average slump of 57 mm (2.25 in.) and an average concrete temperature of 17°C (62°F).

5.3.23 LC-HPC Bridge 13

The thirteenth LC-HPC bridge deck let in Kansas (LC-HPC-13) is the northbound bridge located on US-69 over the BNSF railroad on the southwest side of Pleasanton, Kansas in Linn County. The contract also contained the companion bridge (Control 13) which is the southbound bridge at the same location. The pre-bid conference for LC-HPC-13 was held on January 8, 2007 in Chanute, Kansas. On January 17, 2007 the contract was awarded to Koss Construction. The bridge construction was subcontracted to Beachner Construction. O'Brien Ready Mix supplied the concrete.

LC-HPC-13 was the eleventh LC-HPC deck completed in Kansas with deck cast on April 29, 2008. Dates related to the construction of LC-HPC-13 are shown in Table 5.23.

Table 5.23 – Construction Dates for LC-HPC-13

Item Constructed	Date Completed
Qualification Batch	none
Qualification Slab for Phase 1	4/16/2008
LC-HPC Deck Placement	4/29/2008
Post-Construction Meeting	6/3/2009

Design. The northbound US-69 bridge over the BNSF railroad is a three-span, steel rolled-beam bridge with integral abutments, jersey barriers, and a 34.8 degree skew. Control 13 is the southbound bridge at the same location.

LC-HPC-13 is 90.10 m (296.6 ft) long with span lengths of 27.5, 35.0, and 27.5 m (90.4, 114.8, and 90.4 ft).

The total width of LC-HPC-13 is 12.95 m (42.5 ft), and it was constructed in a single placement. The deck is monolithic with a total depth of 220 mm (8.7 in.), 75 mm (3 in.) of top cover, and 35 mm (1.4 in.) of bottom cover. The top mat of reinforcing steel consists of No. 16 (No. 5) bars spaced at 180 mm (7.1 in.).

Concrete. O'Brien Ready-Mix provided the concrete for LC-HPC-13. For the LC-HPC deck, the average time from loading to discharge was 18 minutes, with a maximum time of 45 minutes and a minimum time of 8 minutes.

The specifications for LC-HPC-13 required a maximum cement content of 317 kg/m^3 (535 lb/yd^3) and a *w/c* ratio of 0.42, for a total paste volume of 23.3%. The cement content was increased to 320 kg/m^3 (540 lb/yd^3) and the *w/c* ratio was increased to 0.44 to aid workability. The qualification slab was cast with a cement content of 320 kg/m^3 (540 lb/yd^3), but because the slump was too high, the cement content for the deck was decreased to 317 kg/m^3 (535 lb/yd^3) using a *w/c* ratio of 0.44 to control slump. The design air content was 8.0%.

The mixture contained three aggregates, including one granite coarse aggregates (BSG_{SSD} = 2.59) from Arkansas and two natural sand fine aggregates (BSG^{SSD} = 2.62). The corral rail mixture for this bridge contained granite coarse aggregate (BSG_{SSD} = 2.59) from Arkansas with a smaller maximum size aggregate.

Qualification Batch. The qualification batch was waived for LC-HPC-13 due to the considerable experience of the ready mix supplier (O'Brien Ready Mix) on LC-HPC-8 and 10.

Qualification Slab Placement (4/16/2008). The qualification slab for LC-HPC-13 was placed on April 16, 2008, and was the first experience the contractor had had with LC-HPC construction. The concrete supplier, however, had previous experience. The slab was constructed on private property with construction starting at approximately 4:00 p.m. and ending at approximately 5:30 p.m., for a total placement time of 1.5 hours. Measured air temperatures during the placement ranged from 22º to 23ºC (71º to 73ºF). The mix design used had a cement content of 320 kg/m^3 (540 lb/yd^3) and a *w/c* ratio of 0.44. The evaporation rate during placement did not exceed 1.0 kg/m^2/hr (0.2 lb/ft^2/hr).

In general, the concrete had slumps greater than allowed by the specifications without using water reducers or plasticizers. The first two trucks had water held out at the plant and a mid-range water reducer added. For LC-HPC construction, specifications now call for all the water to be added at the plant (primarily to limit compressive strength), and once this was done the slumps increased to greater than 100 mm (4 in.) with no water reducers added. For the concrete tested on the deck (after the pump), the average slump was 112 mm (4.4 in.) and the average air content was 6.2%. An air cuff was used at the pump discharge to reduce losses through the pump, and there did not appear to be any loss through the pump.

The average concrete temperature was 23ºC (73ºF) with temperatures ranging from 21º to 24ºC (70º to 75ºF). There are no strength results for the concrete placed in the qualification slab.

Consolidation equipment consisted of two sets of gang vibrators mounted on the same rails on a work bridge separate from the finishing equipment. Each set of gang vibrators contained only three vibrators. The sets were manually operated and moved along the rails to consolidate the concrete.

Finishing was completed with a double-drum roller screed that had one roller removed, a pan drag, and bullfloating. Bullfloating was used because the pan drag did not appear to completely finish the surface. Also, the owner of the private property intended to use the slab as a floor for a building, so they finished the surface more than for a bridge deck to achieve a very smooth surface. There was no fogging equipment present, machine-mounted or hand-held, at the qualification slab. It was intended that the fogging equipment would be qualified at a later date.

The burlap was placed between two work bridges, one of which was attached to the finishing bridge. This caused difficulty in placing the burlap when the second bridge fell behind the finishing. Initially, two layers of burlap was placed at the same time. The workers were instructed to place the burlap layers separately. They did so. The width of the qualification slab was 12.8 m (42 ft), whereas the bridge deck width is 15.9 m (52 ft). For the qualification slab, the burlap pieces reached the full width of the slab, so it could be placed with only one strip. There was some concern that if two pieces would need to be used to cover the full width of the deck, then the burlap placement would be slower. It is not clear why the qualification slab was not the same width as the bridge. There are no construction records regarding rewetting the burlap, and the saturation condition of the burlap prior to placement.

The burlap placing times ranged from 6 to 25 minutes, with an average of 14 minutes. The time to burlap placement exceeded the 10-minute maximum at 9 of 13 stations (69%) timed along the deck, with times ranging from 12 to 25 minutes.

The average haul time from loading to discharge is not known.

Deck Placement (4/29/2008). The placement of LC-HPC-13 occurred on April 29, 2008, with construction starting at approximately 11:15 am and ending at approximately 6:30 p.m., for a total placement time of 7.25 hours. Measured air temperatures during the placement ranged from 17º to 22ºC (63º to 72ºF). The mix design used had a cement content of 317 kg/m^3 (535 lb/yd^3) and a *w/c* ratio of 0.44. The evaporation rate during the placement did not exceed 0.5 kg/m^2/hr (0.1 lb/ft^2/hr).

Overall, the construction went well.

The supply of concrete during the day was generally continuous, with disruption in delivery at the end of the placement when the contractor had to backorder concrete.

Most of the concrete met specifications throughout the placement. All of the concrete in the deck had an air content between 6.5% and 9.5%. Only two trucks had a slump higher than 100 mm (4.0 in.), with slumps of 115 mm and 125 mm (4.5 in. and 5.0 in.). There was some inconsistency with the slump measurement methods, with one inspector's methods possibly increasing the slump readings. The air contents ranged from 6.8% to 9.5% with an average air content of 8.0% for the placement. The slump ranged from 45 to 125 mm (1.75 to 5.0 in.) with an average slump of 75 mm (3.0 in.). The air-entraining agent dosage was increased several times throughout the placement to address decreasing air contents. The concrete temperature ranged from 19º to 22ºC (66º to 72ºF) with an average of 21ºC (70ºF). The concrete test results from the deck indicate that the concrete achieved a compressive strength of 29.5 MPa (4280 psi) at 28 days. For the last 5 truckloads, 2.5 L/m^3 (0.5 gal/yd^3) water was withheld because it was believed that the moisture content of the coarse aggregate was higher at the bottom of the pile.

Placement was from south to north. Discharging the concrete into the concrete pump took an average of 5 or 6 minutes per truck. Two pumps were used to place LC-HPC-13, and concrete with slumps as low as 45 mm (1.75 in) pumped with no problems. When the contractor switched to the second pump, there was a delay due to a switch that had been accidentally turned off. Three trucks waited for about

15 minutes while the problem was solved. An air cuff was used at the pump discharge to limit the air loss through the pump. At the end of the placement, the first pump was used to pre-fill the abutment while the second pump was still filling the deck about 40 ft from the abutment. The delays due to backordering concrete caused a delay in finishing the end of the deck in spite of this proactive preparation.

The concrete was consolidated using two sets of gang vibrators consisting of three vibrators mounted on a work bridge separate from the finishing bridge, as shown in Fig. 5.38. Workers walked between the consolidation bridge and the finishing bridge in the consolidated concrete prior to strike off.

Fig. 5.38 Two sets of gang vibrators mounted on work bridge separate from finishing bridge with worker walking in consolidated concrete

The finishing screed and work bridges were set at the same skew as the bridge. Finishing operations went smoothly, and the deck surface was finished with a double-drum roller screed and a pan drag. This marks the first use of a double-drum roller screed on an LC-HPC decks in Kansas. A wide burlap drag (full width of the deck) was used for about 10 m (30 ft) early in the deck placement, but was stopped because it caused ponded water to be worked into the surface of the plastic concrete. Bullfloating was used for the first half of the placement. Bullfloating was not done for the second half of the placement because after the fogging was turned off the equipment leaked onto the surface of the deck.

The fogging equipment was mounted to the finishing bridge. It consisted of nozzles connected with solid pipe. When the system was turned on the fogging worked well and produced a fine fog in the air above the concrete surface. When the system was turned off, water continually dripped from the system.

At the beginning of the placement, the burlap had dried significantly, so the contractor sprayed water on the burlap before it was placed. Later, the burlap was re-soaked in a water tank and lifted to the deck dripping wet with a crane. After the burlap was placed, the workers kept it wet by spraying it with water excessively so that ponding occurred along the east edge of the deck. The burlap placement was generally slow. Because the burlap was placed within 1.5 m (5 ft) of the finishing equipment, the rate of burlap placement depended on the rate of finishing. The contractor increased the placement rate from 46 m^3/hr (60 yd^3/hr) for the first half of the bridge to 50–54 m^3/hr (65–70 yd^3/hr) for the second half, so the burlap placement rates generally decreased.

The burlap was placed from two work bridges following the finishing bridge. The burlap placing times ranged from 2 to 24 minutes, with an average of 12 minutes. The time to burlap placement exceeded the 10-minute maximum at 17 of 31 stations (55%) timed along the deck, with times ranging from 11 to 24 minutes. The burlap was kept wet by spraying water with the hose after it was placed. The workers were asked reduce the amount of water sprayed on the burlap because water was ponding on the east side of the bridge deck.

The average haul time from loading to discharge was 18 minutes, with times ranging from 8 to 45 minutes. The last two trucks were backordered and caused a wait of over an hour. The crews were slow in covering the deck with burlap for the last 3 m (10 ft) of the deck. The time to burlap placement ranged from 14 to 18 minutes for the last 5.5 m (18 ft) of the deck.

For this bridge, the contractor followed the LC-HPC cold weather curing specifications as they were let for this project, except they followed the new Phase 2 specifications regulating the time of start up during cold weather conditions. The air temperatures during the night before the placement were below 4ºC (40ºF) and were predicted to rise above 16ºC (60ºF) during the day of the placement. Therefore, the contractor waited until the air temperature had risen to 10ºC (50ºF) before starting to place concrete in the deck. This was the first time that the start up requirements during cold weather portion of the Phase 2 specifications were used. Air temperatures remained above 4ºC (40ºF) during the 14-day curing period and protection of the deck and girders was not required.

The jersey barriers were cast on June 20 and July 10, 2008. Deck forms were removed on days 72, 94, 97–101, 105, 107, 113–115, and 118–122 after the LC-HPC-13 deck placement.

Unique Considerations. This was the first and only LC-HPC bridge deck placed by this contractor.

Personnel Response and Post-Construction Conference (6/3/2009). Representatives from the contractor, KDOT and KU were present to discuss the results of the LC-HPC bridge deck placement. The contractor indicated that presoaking the burlap worked well and they kept it wet after placement. Also, they thought the concrete finished well with the bullfloat. KU indicated that burlap was not always saturated when it was placed. The item of greatest concern was that concrete was backordered twice causing a delay of over an hour at the end of the placement. KDOT representatives indicated that ways to encourage ordering enough concrete and avoid the long delays include providing an incentive to the contractor to complete the deck without backordering concrete and paying for the direct cost (not including labor) of any overrun concrete.

Lessons Learned. Concrete material cost is a primary concern for the contractor, and they will tolerate delays at the end of a placement to avoid purchasing more concrete than needed.

5.3.24 Control Bridge 13

Control 13 is the southbound portion of the bridge located on US-69 over the BNSF railroad on the southwest side of Pleasanton, Kansas in Linn County. The contract also contained the companion northbound bridge at the same location (LC-HPC-13). The pre-bid conference for Control 13 was held on January 8, 2007 in Chanute, Kansas. On January 17, 2007 the contract was awarded to Koss Construction. The bridge construction was subcontracted to Beachner Construction. O'Brien Ready Mix supplied the concrete.

Control 13 was completed on July 25, 2008. Dates related to the construction of Control 13 are shown in Table 5.24.

Table 5.24 – Construction Dates for Control 13

Item Constructed	Date Completed
Subdeck	7/11/2008
Silica Fume Overlay	7/25/2008

Design. The southbound US-69 bridge over the BNSF railroad is a three-span, steel rolled-beam bridge with integral abutments, jersey barriers and 34.8 degree skew. LC-HPC-13 is the companion southbound bridge at this location.

Control 13 is 90.10 m (296.6 ft) long with spans that are 27.5, 35.0, and 27.5 m (90.4, 114.8, and 90.4 ft) long.

The total width of Control 13 is 12.95 m (42.5 ft), and the deck was constructed in two placements – the subdeck and the silica fume overlay (SFO). The Control 13 deck is a two coarse, silica fume overlay deck with a total depth of 220 mm (8.7 in.), 75 mm (3 in.) of top cover, and 30 mm (1.2 in.) of bottom cover. The subdeck is 180 mm (7.1 in.) thick and the silica fume overlay is 40 mm (1.6 in.) thick. The top mat of reinforcing steel consists of No. 16 (No. 5) bars spaced at 180 mm (7.1 in.).

Concrete. The concrete mix designs for both the subdeck and the SFO meet the KDOT specifications for this type of structure. The concrete mix for the subdeck contained 363 kg/m^3 (611 lb/yd^3) of Type I/II cement, a *w/c* ratio of 0.40, and an air content of 6.5%. The aggregate used in the subdecks was a 50:50 blend of natural sand (BSG_{SSD} = 2.62) and limestone (BSG_{SSD} = 2.60). The silica fume overlay concrete included a 7% silica fume replacement of cement, or 26 kg/m^3 (44 lb/yd^3), 350 kg/m^3 (589 lb/yd^3) of Type I/II cement, a *w/cm* ratio of 0.37, and an air content of 6.5%. Quartzite (BSG_{SSD} = 2.63) from South Dakota was used as the coarse aggregate.

Subdeck (7/11/2008). The subdeck for Control 13 was cast on July 11, 2008 with recorded air temperatures ranging from 23° to 30°C (73° to 86°F). Placement started at approximately 1:45 p.m. and was completed by about 10:00 p.m.

The concrete test results for the subdeck placement indicate an average air content of 5.8%, an average slump of 91 mm (3.6 in.), and an average concrete temperature of 32°C (89°F). The average haul time was 21 minutes from loading to discharge. Form removal dates were not obtained for Control 13.

Silica Fume Overlay (7/25/2008). The SFO for Control 13 was cast on July 25, 2008 with a recorded air temperature of 29°C (84°F).

The two concrete test results for the SFO placement indicate an average air content of 6.3%, with a minimum of 6.1% and a maximum of 6.5%. The average slump was 133 mm (5.25 in.) with a minimum of 97 mm (3.8 in.) and a maximum of 168 mm (6.6 in.). Both tests indicate a concrete temperature of 33°C (91°F). The average haul time was 14 minutes from loading to discharge.

5.3.25 LC-HPC Bridge 14

The fourteenth LC-HPC bridge deck let in Kansas (LC-HPC-14) is the Metcalf Avenue over Indian Creek bridge located in Overland Park, Kansas. Contracted by the City of Overland Park, Kansas, the project contained one bridge and was awarded to Pyramid Construction. LC-HPC-14 was constructed in two phases. For Phase 1, there was one failed attempt at the deck placement and one successful deck placement. Phase 2 consisted of two deck placements. LC-HPC-14 was the twelfth LC-HPC deck completed in Kansas with construction spanning more than three months. Dates related to the construction of LC-HPC-14 are shown in Table 5.25.

Table 5.25 – Construction Dates for LC-HPC-14

Item Constructed	Date Completed
Qualification Batch	none
Qualification Slab	11/13/2007
LC-HPC Deck - Phase 1 attempt 1 (center)	11/19/2007
LC-HPC Deck - Phase 1 attempt 2 (center)	12/19/2007
LC-HPC Deck - Phase 2 West	5/2/2008
LC-HPC Deck - Phase 2 East	5/21/2008
Post-Construction Meeting	3/4/2008

Design. The Metcalf Avenue bridge over Indian Creek is located in Overland Park, Kansas just north of the Metcalf Avenue and 103rd Street intersection. It is a three-span, rolled steel girder bridge with integral abutments, corral rails, and an 18 degree skew. The bridge construction was constructed in two phases with three separate placements. The first phase (or “stage”) of construction consisted of the center portion of the deck, with a deck width of 18.3 m (60 ft). The second phase of construction consisted of two placements, one on each side of the phase 1 (center) placement. The second placement (Phase 2 West) was the west portion of the deck and was 14.5 m (47.5 ft) wide. The third placement (Phase 2 East) was the east portion of the deck and was 9.9 m (32.5 ft) wide. The total width of the Metcalf Avenue bridge is 42.67 m (140.0 ft). Corral rails separate the driving surface from the walking surface for both the west and east placements and are located 2.3 m (7.5

ft) and 3.2 m (10.5 ft) from the edges of the deck, respectively. The three placements are connected by construction joints.

LC-HPC-14 is 66.33 m (217.6 ft) long, with three span lengths from the south abutment (Abutment #1) to the north abutment (Abutment #2) are 20.5 m (67.3 ft), 25.3 m (83.0 m), and 20.5 m (67.3 ft).

The LC-HPC-14 deck is monolithic with a total depth of 216 mm (8½ in.), 75 mm (3 in.) of top cover, and 25 mm (1 in.) of bottom cover. The top mat of reinforcing steel consists of No. 19 (No. 6) bars spaced at 178 mm (7 in.).

Concrete. The ready mix supplier for LC-HPC-14 was the same as for LC-HPC-3 through 6, which were being completed at the same time. Therefore, a qualification batch of concrete was not required for LC-HPC-14. Originally, the alternate mix used for LC-HPC-4 and 5 was planned for use on LC-HPC-14 with a *w/c* ratio of 0.42 and a cement content of 317 kg/m^3 (535 lb/yd^3). Many of the same difficulties encountered in the previous bridges were encountered during the construction of LC-HPC-14. After the first attempt of the first placement of LC-HPC-14 failed, as described later, on November 19, 2007 due to a blown gasket in the concrete pump, the mix design was changed to a *w/c* ratio of 0.45 and conveyors were used for the remainder of the placements.

The design air content was 8.0%. The mixture contained three aggregates, including two granite coarse aggregates (BSG_{SSD} = 2.61) from Arkansas, one manufactured (crushed granite) sand (BSG_{SSD} = 2.61) from Arkansas, and one natural river sand fine aggregate (BSG_{SSD} = 2.61).

Qualification Batch. A qualification batch was not required for LC-HPC-14 because the ready-mix supplier was concurrently supplying concrete to LC-HPC-3 through 6 on a separate project, and the same concrete was planned for use on LC-HPC-14.

Qualification Slab (11/13/2007). The qualification slab was completed on Tuesday November 13, 2007, with placement beginning at approximately 2:00 p.m. The placement was completed in approximately 3 hours. The air temperatures during placement ranged from 18° to 21° C (65° to 69°F), and for the day from 4° to 19°C (39° to 66°F). The qualification slab was 9.1 m (30 ft) wide, only half of the width of the first deck placement. During the placement of the qualification slab the contractor asked many questions regarding LC-HPC procedures. This communication is documented in this section. This is an example of how the qualification slab is beneficial for the contractor to understand and practice the procedures before the deck placement.

The wrong concrete was delivered and placed for the qualification slab. LC-HPC-3 was placed earlier on the same day with a *w/c* ratio of 0.45, and concrete produced by the same ready-mix supplier. Because the same ready-mix plant and personnel were providing the concrete for both projects, which were planned and approved to have the same concrete (*w/c* ratio of 0.42), the supplier delivered the same concrete to the LC-HPC-14 qualification slab (*w/c* ratio = 0.45) as was placed on LC-HPC-3 earlier in the day, even though the change from a *w/c* ratio of 0.42 to 0.45 was not approved for LC-HPC-14. Because KU personnel were not aware of the change in *w/c* ratio from 0.42 to 0.45 for LC-HPC-3 and 6, there was confusion as to why a 0.45 *w/c* ratio mixture was delivered to the LC-HPC-14 qualification slab. With the 0.45 *w/c* ratio, the pumping and finishing went well. When KU personnel and city officials learned that the concrete had the wrong *w/c* ratio, they decided to order one more truck with the correct *w/c* ratio (0.42) and check to make sure it also placed and finished adequately. The 0.42 *w/c* ratio mixture had an air content of 7.4% and a slump of 75 mm (3.0 in.) and it also finished well and had no problems with pumping.

The average slump of the concrete placed in the qualification slab was 75 mm (3.0 in.), with a minimum of 70 mm (2.75 in.) and a maximum of 95 mm (3.75 in.). The average air content was 7.6% with a minimum of 7.4% and a maximum of 8.5%. The concrete temperature ranged from 20º to 21ºC (68º to 70ºF) with an average of 14ºC (57ºF). Concrete testing was performed from samples taken at the trucks. The fourth truck (of six) was not tested. A plan for testing concrete for the deck placement was decided. The first three trucks would be tested from the truck, and the rest of the concrete would be tested from the deck. If the concrete, tested on the deck, did not meet specifications, then the next truck would be tested from the truck until the concrete meets specifications.

The pump discharge did not have an air cuff or an "S-Hook" to limit air loss in spite of a long drop. The contractor indicated that he would have one for the deck placement.

The contractor asked about consolidation and if the concrete should be vibrated longer. He was asked to demonstrate their normal procedures. The contractor's originally demonstrated procedures did not provide adequate consolidation, as shown in Fig. 5.39. Upon inspection, the contractor was instructed to leave the vibrators in the concrete at least 2 to 3 seconds or until the coarse aggregate dropped below the concrete surface.

Fig. 5.39 Coarse aggregate particles above the concrete surface indicates concrete is underconsolidated and holes in the concrete from where vibrators were located, indicating that the vibrators were removed too quickly leaving no coarse aggregate at the insertion points

The concrete (both the 0.42 and 0.45 *w/c* ratio mixtures) finished well with a double-drum roller screed with one roller removed and a pan drag. Some bullfloating was also performed. The contractor asked whether bullfloating was desired, and they were told that a pan drag or burlap drag had worked well for other placements. It was emphasized that no water may be used as a finishing aid.

The fogging equipment was mounted on the back of the finishing bridge. The system consisted of solid pipe connecting 9 spray nozzles and was 9.1 m (30 ft) long, matching the qualification slab. The full length of the fogging system, 18.2 m (60 ft), would be requalified on the day of the deck placement. The system did not drip on the concrete surface except when the wind blew the mist onto the hose and the condensed water dripped.

Rail reinforcement was not present or simulated in the qualification slab.

The contractor asked if the two layers could be placed at the same time, and they were told that two layers may be placed simultaneously if the burlap overlapped at all locations and was placed within 10 minutes. The burlap was presoaked and two layers were placed simultaneously after finishing. Even though the burlap was placed directly following the finishing equipment, the burlap placement times did not meet the 10-minute requirement due to the concrete delivery rate. The workers did a good job of keeping the burlap wet after it was placed. The contractor was asked if they would use the same crew for placing burlap as they did for the qualification slab and was asked to dedicate a supervisor to the burlap placement operation during the deck placement.

Because they planned to wrap and heat the deck, the contractor was concerned about the deck overheating during the curing period and asked if the heaters may be turned off during the curing period to regulate the temperature. They were told that the heaters may be turned off to keep the temperatures within the specified limits.

A post-qualification meeting was held to discuss the upcoming deck placement. The contractor stated he would have two pumps on site for the deck placement, one of which would be the same as used on the qualification slab. Cores from the qualification slab indicated significant limestone contamination in the concrete. The concrete supplier said that the aggregate bins had been cleaned. The supplier also discussed previous deck placements, indicating that the moisture contents had been off so that the resulting (as placed) *w/c* ratios could be as much as 0.03 lower than as designed. The supplier indicated that special care would be taken to determine accurate free surface moisture values for the LC-HPC-14 deck placement.

A concrete pump test was performed on Friday November 16, 2007 with KU personnel in attendance. The concrete met specifications with a slump of 38 mm (1.5 in.), air content of 8.5%, and concrete temperature of 16°C (60°F), and pumped adequately with a 42-m pump with the pump boom positioned straight up and down. The air content after the pump was 5.6%. There was stopping and starting with the pumping, which increased the effort required, so the importance of a continuous stream of concrete during the deck placement was discussed. The contractor also wanted to try pumping concrete with a higher slump, so superplasticizer was added to the truckload. After the admixture was added, the slump was 200 mm (8 in.), and it was not retested after the pump.

The contractor, inspectors, and Overland Park personnel were satisfied that the concrete could be pumped with a 38-mm (1.5-in.) slump, but based on the LC-HPC-5 deck placement on Wednesday November 14, 2007, it was clear that it was not possible to pump many trucks with a slump of 38 mm (1.5 in.). Everyone agreed that a slump of 75 mm (3 in.) was important. The pump operator indicated that two 47-m pump trucks would be at the deck placement, which was not the same size pump as used for this concrete pump test.

Deck Placement 1 attempt 1 - Phase 1 Center (11/19/2007). The first attempt at placement 1, on November 19, 2007, was a failure. The placement was eventually halted after 3 hours and only 30 ft of placement due to various problems with concrete not meeting specifications and an inability to pump the concrete. Ultimately a gasket was blown in the concrete pump, the placement was cancelled, and the concrete was eventually removed from the deck.

Construction began at 6:00 p.m. with the direction of placement being from south to north. Air temperatures on the day of placement ranged from 4º to 19ºC (39º to 66ºF). As planned, the concrete mixture had a *w/c* ratio of 0.42.

The first several concrete trucks to arrive on the site had a high air content and slump, so they were held to wait for retesting. They were retested and met specifications, but one truck was rejected because it exceeded the maximum time limits. By the time concrete was being placed in the deck, the concrete slump was very low and the concrete was difficult to pump. Concrete pumping was not continuous, with lots of starting and stopping. Concrete property measurements before and after the pump indicated that the air loss through the pump was approximately 2.0%, and the slump loss was approximately 25 mm (1 in.). No measures were taken, such as an "S-Hook" or an air cuff at the pump discharge, to limit air loss through the pump. Eventually, the pump blew a gasket and by the time the repairs were made, the lines were clogged and the placement was cancelled.

Results for concrete tested from the truck and placed in the deck indicated that the slump ranged from 45 to 135 mm (1.75 to 5.25 in.) with an average of 93 mm (3.6 in.). Air contents ranged from 7.8% to 9.7% with an average of 8.7%. One truckload placed in the deck had an air content of 5.7%, below the specified minimum of 6.5%. The concrete surface temperature ranged from 16º to 21ºC (60º to 69ºF) with an average of 18ºC (65ºF).

The location for the concrete pump and truck delivery was narrow, allowing only one truck to discharge to the pump at a time. This also aggravated the start and stop nature of this placement.

Because of the significant difficulties with concrete and pumping, the focus of this placement attempt was on those portions of the placement. Even though the completed portions of the deck for this placement attempt were ultimately torn out and not part of the completed deck, the following construction techniques are documented next.

The concrete did not finish well with the double-drum roller screed with one roller removed and pan drag. Bullfloating was necessary, but at times a smooth finish still could not be achieved. Water was not used as a finishing aid for this placement.

The fogging system was turned on during delays in the concrete delivery. The fogging equipment dripped on the concrete. Water from the fogging equipment and fog spray accumulated on the deck surface.

A meeting was held on November 20, 2007, with representatives from the contractor, the concrete supplier, the City of Overland Park, the structural designer and the pumping company. The contractor stated that they would tear out the concrete. It was decided to use a conveyor belt instead of a pump for the next placement attempt. There was much discussion about acceptance criteria of concrete for the next placement, but no decisions were made at this meeting.

Deck Placement 1 attempt 2 - Phase 1 Center (12/19/2007). The second attempt at placement 1 was successfully completed on December 19, 2007 using a conveyor belt rather than a pump. Placement began at 9:00 a.m. and the last burlap was placed at approximately 4:10 p.m. for a total placement time of just over 7 hours.

The average placement rate was approximately 37 m^3/hr (48 yd^3/hr). Air temperatures during the placement ranged from 3º to 14ºC (37º to 57ºF), with a minimum and maximum air temperature of –3º and 8ºC (26º and 47ºF) for the day according to weather station data. Air temperatures dropped below freezing on all of the days during the 14-day curing period except day 3, and below 4ºC (40ºF) on all of the 14 days.

The concrete mix design was changed, increasing the *w/c* ratio to 0.45. Concrete test results indicated that the slump ranged from 44 to 133 mm (1.75 to 5.25 in.) with an average of 91 mm (3.6 in.). Air contents ranged from 7.6% to 9.7% with an average of 8.7%. The concrete temperature ranged from 16º to 21ºC (60º to 69ºF) with an average of 18ºC (65ºF).

Concrete was tested from the trucks at a location on 103rd Street, usually about 15 minutes before the concrete was placed in the deck. Testing was performed every

5 trucks (every 50 yd^3), and concrete with slumps up to 125 mm (5 in.) was allowed to be placed in the deck. One truckload had a slump of 125 mm (5.25 in.) and was placed in the deck without retesting after the conveyor. The next truckload had a slump of 145 mm (5.75 in.). This truck was immediately retested by a different crew member and the test results indicated a slump of 100 mm (4 in.). The rest of the testing was performed by the same individual, and the rest of the concrete had slumps that met specifications.

Placement was from south to north. The concrete in the abutment was retained from the first attempt at the placement on November 19. 2007.

The conveyor placed concrete in the deck with a drop of approximately 3.7 to 4.6 m (12 to 15 ft), resulting in an air loss of 2% to 2.5%.

For this placement, consolidation procedures were again inadequate. Coarse aggregate remained visible at the concrete surface after the vibrators were removed. Because the vibrators were removed too quickly from the concrete, with a jerking motion, a hole was left in the concrete with a "lip" around each vibrator insertion point, as shown in Fig. 5.40.

The concrete was finished with a double-drum roller screed with one drum removed, a pan drag, and a bullfloat. Bullfloating was performed perpendicular to the work bridge as shown in Fig. 5.41. Bullfloating in this direction is generally slower and requires larger distances between the work bridge and the finishing equipment, both of which increase the time to burlap placement and increases the exposure of the concrete to drying conditions. The surface finish after the screed was adequate, as shown in Fig. 5.42, but the early in the placement, the screed left some regions with coarse aggregate particles showing. The contractor worked hard to finish those regions by adding additional concrete and providing additional bullfloating. For the rest of the placement, he bullfloated the surface, although it was not necessary. Two contractor personnel indicated that a double-drum roller screed with both drums would have been able to finish the concrete with no additional bullfloating. Overall,

Fig. 5.40 Coarse aggregate particles and a consolidation lip at the locations of vibrator insertion indicate inadequate consolidation

Fig. 5.41 Bullfloating performed perpendicular to finishing bridge is slower and causes delays in burlap placement.

Fig. 5.42 The surface finish after the screed was acceptable and bullfloating was not necessary

the contractor spent considerable effort finishing the deck, and the deck boardered on being overfinished.

The fogging equipment was turned on for most of the placement. The wind blew the fogging mist back onto the equipment, and subsequentially dripped onto the surface of the deck. Some of the accumulated water was bullfloated into the surface of the deck.

Because of the delays due to finishing the deck, waiting for concrete, and the large width of the placement, the time to burlap placement exceeded the maximum requirements, at times exceeding 40 minutes. The placement times decreased throughout the placement, but always exceeded 20 minutes. The burlap placing times ranged from 20 to 40 minutes, with an average of 28 minutes. The burlap placement never met the 10-minute requirement at any of the 18 stations timed along the deck.

There were 13 workers placing burlap. Six workers placed the burlap from the work bridges, four moved the work bridges, one delivered the burlap, and two kept the burlap wet after it was placed. Three pieces of burlap were required to reach across the entire placement. In the beginning, workers placed two layers of burlap at the same time, and later they switched to placing single layers.

Cold weather concreting specifications were in effect for this placement. The bridge was enclosed underneath with plastic sheeting and heated. Eight heaters, four on each side of Indian Creek, were hung from the girders and used to heat the air under the deck. The installation of the heaters was not completed until 9:30 a.m., after concrete placement had begun. The air temperature under the deck was measured prior to and periodically during placement. The air temperature at the girders was 6°C (42°F) at 9:00 a.m. and 18 (65°F) at 10:00 a.m. Unfortunately, the temperature was not monitored continuously and immediately following concrete placement, and Overland Park personnel reported a maximum temperature of 29°C (85°F) under the deck on the evening of December 19, 2007. After the day of placement, Overland Park personnel reported that the air temperatures were maintained within the required range between 13° and 21°C (55° and 70°F) for the remainder of the 14-day curing period.

Deck Placement 2 - Phase 2 West (5/2/2008). The second placement of LC-HPC-14 was completed on May 2, 2008. Placement began at 9:15 a.m. and the last burlap was placed at approximately 4:00 p.m. for a total placement time of approximately 6.75 hours.

The average placement rate for the placement was approximately 31 m^3/hr (40 yd^3/hr). The air temperature measured during the placement was 14º (58ºF). The minimum and maximum air temperatures for the day were 12º and 28ºC (53º and 83ºF) according to weather station data. Air temperatures remained above 4ºC (40ºF) throughout the curing period.

The concrete mix design was the same as for placement 1 with a *w/c* ratio of 0.45. The concrete placed in the deck generally had high slump and high air content. The concrete supplier indicated that the heavy rain from the night before caused some difficulties in determining the moisture content of the aggregates. Concrete testing occurred prior to placement on the deck using a conveyor belt. Two truckloads were tested before and after the conveyor belt. The air losses were 1.4% and 2.4%, and the slump losses were 20 mm (0.75 in.) and 15 mm (0.5 in.). These losses were used as an excuse to not reject concrete with a high slump or high air content or both. Concrete test results indicated that the slump ranged from 65 to 150 mm (2.5 to 6 in.)

with an average of 109 mm (4.3 in.). Air contents ranged from 7.0% to 11.0% with an average of 9.8%. The concrete temperature ranged from 17º to 18ºC (63º to 65ºF) with an average of 18ºC (64ºF). Overland Park personnel indicated that the concrete was "perfect" with a slump of 115 mm (4.5 in.) and an air content of 10% to 10.5%.

It was unfortunate that the Overland Park officials were influenced by the contractor to accept concrete with slumps that exceeded the maximum allowable slump of 100 mm (4 in.). As a result, the LC-HPC-14 placements are likely at increased risk for settlement cracking.

On May 20, 2008, KU personnel received a call from Overland Park officials reporting that the compressive strength of the concrete placed in the south abutment during the second placement was approximately 18.6 MPa (2700 psi), lower than the specified strength of 27.6 MPa (4000 psi). Limited core testing indicated that in-place strengths were above 27.6 MPa (4000 psi).

There was no interruption of concrete delivery throughout the placement except for the first four trucks and the last 2 trucks.

The second placement of LC-HPC-14 went relatively smoothly. Concrete was placed in the deck with a conveyor belt located on placement 1. The direction of placement was from south to north. The concrete was finished using a double-drum roller screed with a pan drag, followed by bullfloating (performed from and in front of the first work bridge), and finally a large burlap drag mounted on the first work bridge and spanning across the entire placement. The two work bridges used for burlap placement followed the burlap drag. LC-HPC-14 placement 2 was the second time a double drum roller screed had been used on an LC-HPC deck. The previous deck placement finished with a double drum roller screed was LC-HPC-13, which was constructed just a few days prior on April 29, 2008.

Bullfloating of the deck was performed on a limited basis, except for the last 9.1 m (30 ft) (north end) of the deck, where bullfloating and hand floating were used extensively because difficulty finishing due to delays from concrete delivery at the end of the placement. A finishing aid was also worked into the surface of the deck in this area. Some ponded water was worked into the surface on the east end of the placement at this location as well. Even with the extra finishing efforts, some voids in the surface of the deck were observed.

The sidewalk portion of the deck was screeded with a piece of 2×4 lumber attached to the finishing bridge. The surface was then bullfloated and finished by hand. The bullfloating slowed down the advancement of the burlap drag work bridge and therefore the burlap placement rates.

Mounted fogging equipment was not used for this placement, but hand fogging was performed once at the end of the deck while waiting for concrete to arrive. This hand fogging resulted in some water ponding on the deck. The estimated evaporation rate for the placement was 0.29 $kg/m^2/hr$ (0.06 $lb/ft^2/hr$).

Burlap placement was slow throughout the day due to bullfloating the sidewalk and the additional work bridge with the burlap drag (added approximately 3 to 5 minutes). The average time between finishing and burlap placement was 21 minutes, with a minimum time of 12 minutes and a maximum time of 74 minutes. All of the 33 (100%) locations timed exceeded the 10 minute requirement. The concrete at 14 of the 33 (42%) locations timed was left exposed to drying for 20 minutes or longer. For the main portions of the deck, the placement rates were approximately 15 minutes except for a few delays due to conveyor belt repositioning. Burlap placement times at the end of the placement increased to values between 40 and 75 minutes for the final 12 m (40 ft) of the deck due to significant delays due to the need to backorder concrete. During the delay some concrete (several cubic feet – not measured) was scavenged (shoveled) out of the wing wall and into the deck, but it was not enough to finish the deck. Concrete was preplaced in the final abutment with a bucket and crane and from the conveyor belt.

One layer of burlap were placed at a time. The in-place burlap was kept by using hoses to spray the burlap several times during the placement.

The burlap placement for the sidewalk was even slower than for the deck because it was placed longitudinally, with one piece placed on the sidewalk after four pieces of burlap were placed transversely along the deck. The placement rates for the sidewalk, therefore, varied widely from 20 to 50 minutes, and at the end of the placement even longer.

During delays in concrete delivery and finishing, the concrete that had been placed in the deck but not finished or struck off was covered with wet burlap during the delay. This occurred at the end of the placement while waiting for the final truckloads of concrete. This is the first case where this method of protecting unfinished LC-HPC concrete occurred. The other instances when this method was used was during the placement of LC-HPC-12 Phase 2 and at the end of LC-HPC-9.

Deck Placement 3 - Phase 2 East (5/21/2008). The third placement of LC-HPC-14 was completed on May 21, 2008. Placement began at 6:00 p.m. and was completed by approximately 9:30 p.m. for a total placement time of 3.5 hours.

The concrete mix design was the same as for placements 1 and 2, with a *w/c* ratio of 0.45. The concrete placed in the deck had very high slump and high air content. It appears that the contractor has influenced the owner to use the higher slump concrete. An Overland Park official indicated that the reinforcement in the deck was not firmly supported and tended to spring up potentially increasing the risk for settlement cracking, particularly for higher slump concrete.

Concrete testing occurred prior to placement on the deck. Two truckloads were tested before and after the conveyor belt. The air losses were 0.5% and 1.2%, and the slump losses were 64 mm (2.5 in.) and 50 mm (2.0 in.). Concrete test results indicated that the slump was very high, ranging from 108 to 165 mm (4.25 to 6.5 in.) with an average of 132 mm (5.2 in.). All of the seven slump tests performed on samples taken from the truck exceeded the maximum allowable value of 100 mm (4.0 in.). Air contents ranged from 8% to 10.5% with an average of 9.7%. Five of eight air content tests exceeded the maximum allowable value of 9.5%. The concrete temperature ranged from 17º to 19ºC (62º to 67ºF) with an average of 18ºC (65ºF). The concrete met the specifications for temperature for all tests.

There was no interruption of concrete delivery throughout the placement. The ready mix trucks discharged into the hopper using a full chute positioned at a low angle for discharge. High slump concrete was necessary to discharge with this method. For other LC-HPC placements with slumps required for LC-HPC, an elevated approach and a half-chute was required for discharge at a steeper angle.

Concrete was placed in the LC-HPC-14 deck with a conveyor belt. Placement was from south to north. The concrete was finished using a double-drum roller screed with a pan drag and a large burlap drag attached to the first work bridge, similar to placement 2. Initially, a bullfloat was used instead of the burlap drag. Due to the high slump concrete, there were no problems with finishing the deck.

The sidewalk portion of the deck was finished using a broom/hydraulic pump mechanism. Fogging was not performed for LC-HPC-14 placement 3.

Burlap placement was slow throughout the day. At one point the time to burlap placement met the specifications with a time of 9 minutes. The average time between finishing and burlap placement was 15 minutes, with a minimum time of 9 minutes and a maximum time of 21 minutes. Nine of ten (90%) of locations timed exceeded the 10 minute requirement, with times ranging from 11 to 18 minutes. Some of the burlap was partially dry when it was placed on the deck. It was sprayed with water to wet it after it was placed. The burlap placement on the sidewalk portion of the deck kept up with placement on the driving surface portion of the deck.

Unique Considerations. There is reason to believe that communication between the contractor for this project and the contractor for the I-435 project influenced the contractor's attitude for this project, particularly after similar pumping problems to the I-435 project were experienced for LC-HPC-14.

Personnel Response and Post-Construction Conference. There was significant pushback from the contractor in many areas. First of all, after the first failed attempt at placement 1, there was considerable pressure on the owner to accept concrete with higher slumps than allowed by the specifications. This ultimately is what happened. Second, even though told to not overwork the surface and cover the concrete as fast as possible, the contractor spent considerable effort and attention to achieving a smooth finished surface and the burlap placement rates were never acceptable for any placement. The contractor was going to do what he wanted to do. It would have required activating stiff penalties or an owner willing to reject concrete and stop construction to change the construction methods of this contractor.

Lessons Learned. Active and aggressive pressure from contractors can significantly influence the owner to accept materials and methods that do not meet specifications.

It is possible for owner's inspectors to continue to resist project specifications requiring lower slump concrete because to do so requires more work on the part of both the contractor and the inspector.

Exposed concrete should be covered with wet burlap during delays. This includes all concrete placed on the deck, finished or unfinished, unconsolidated concrete, and concrete under the finishing bridge.

It is important to maintain positive and open lines of communication with contractors during and after placement of LC-HPC. Each job can affect future jobs because of this and communication about experiences. The contractor's perceived experience with LC-HPC can impact projects outside of the current project.

5.3.26 Control Bridge Alternate

Control Alternate, or Control Alt, is the bridge over US-69 on K-52 in Emporia, Kansas. Control Alt was not originally part of this study, but was selected as an additional control structure because it is a monolithic deck.

On March 16, 2005, the contract was awarded to King Construction. Builders Choice supplied the concrete. The deck construction for Control Alt was completed on June 2, 2005. Dates related to the construction of Control 13 are shown in Table 5.26.

Table 5.26 – Construction Dates for Control Alt

Item Constructed	Date Completed
Deck	6/2/2005

Design. The K-52 highway bridge over US-69 is an existing four-span, steel rolled-girder bridge with non-integral abutments, corral rail style barriers, and a 21.5 degree skew.

Control Alt is 54.7 m (179.6 ft) long with the four spans of 12.1, 15.2, 15.2, and 12.1 m (39.8, 50.0, 50.0, and 39.8 ft).

The total width of Control Alt is 9.75 m (32.0 ft), and it was constructed in one placement. The monolithic deck has a total depth of 216 mm (8.5 in.), 64 mm (2.5 in.) of top cover, and 25 mm (1.0 in.) of bottom cover. The top mat of reinforcing steel is No. 19 (No. 6) bars spaced at 165 mm (6.5 in.).

Concrete. The concrete mix designs for the monolithic deck include 357 kg/m^3 (602 lb/yd^3) of Type I/II cement, a *w/c* ratio of 0.40, and an air content of 6.5%. The aggregate used in the decks was a 50:50 blend of natural sand (BSG_{SSD} = 2.62) and limestone (BSG_{SSD} = 2.60

Deck (6/2/2005). The monolithic deck for Control Alt was cast on June 2, 2005 with air temperatures for the day ranging from 16° to 25°C (60° to 77°F). Placement started at approximately 6:00 a.m. and was completed by about 10:00 a.m., for an average placement rate of 38 m^3/hr (50 yd^3/hr).

The concrete test results for Control Alt indicate an average air content of 5.9% and an average slump of 75 mm (3.0 in.). The concrete temperature was not recorded for Control Alt. The average haul time was 51 minutes from loading to discharge. Form removal dates were not obtained for Control Alt.

5.4 CRACK SURVEY RESULTS AND EVALUATION

The performance of low-cracking high-performance concrete (LC-HPC) bridge decks is evaluated based on crack densities measured in the field. These crack densities are obtained from surveys that conform to the specifications for crack surveys outlined by Lindquist et al. (2005). The crack density data for LC-HPC decks are compared to crack densities obtained for control decks surveyed as a part of this study and to data collected for earlier surveys of bridge decks in Kansas by Schmidt and Darwin (1995), Miller and Darwin (2000), and Lindquist et al. (2005). The influence of variables related to structure type, site conditions (including air and concrete temperature), and construction methods are analyzed by comparing variables from these categories with crack densities from this and previous studies. The preliminary crack density results for the individual LC-HPC bridge decks and the effects of deck age, deck type, and material properties are discussed in the companion report by Lindquist et al. (2008).

This section is divided into five parts. Section 5.4.1 examines the effect of age on bridge deck cracking. Section 5.4.2 compares the cracking performance of various structure types. Section 5.4.3 examines the effect of various site conditions, including concrete temperature, Section 5.4.4 compares the effects of various construction methods, and Section 5.4.5 evaluates the effect of the contractor and the contractor's experience with LC-HPC construction. The results are presented using projected crack densities, which represent the expected level of cracking at an age of 78 months (6.5 years). A discussion of the age-correction procedure and the raw crack density data are provided by Lindquist et al. (2008).

This analysis includes crack survey data for a total of seven LC-HPC and seven control bridge decks for this study, as well as data for monolithic decks from the three previous Kansas studies mentioned above. All of the bridges supporting the monolithic LC-HPC decks have steel girders. For the seven control decks, five are silica fume overlay (SFO) decks supported by steel girders, one is a monolithic deck with steel girders, and one is a monolithic deck with prestressed girders. Because little is known regarding the rate of cracking in prestressed girder bridges, an age-corrected crack density cannot be determined for the single control bridge with prestressed girders. The crack density data used in this analysis are presented Table E.1.

5.4.1 Bridge Deck Cracking Versus Bridge Age

The crack density results for the 14 bridge decks (7 LC-HPC and 7 Control decks) surveyed to date are plotted versus bridge age in Fig. 5.43. The bridge decks range in age from 5 to 37 months with an average age of 16 months. For bridge decks constructed in two placements (e.g. for an overlay deck), the bridge age is calculated as the difference between the survey date and the date of the last concrete placement. Data points connected by lines indicate bridge decks that have been surveyed more than once. Crack density results represent the crack density for the entire deck surface, with two exceptions. LC-HPC-4 was cast in two placements with different concrete mix designs, and Control 7 consists of two placements that were constructed approximately six months apart. These two bridges are treated separately, each with different crack densities.

The crack densities for the control decks exhibit substantial scatter, ranging from 0.000 to 0.665 m/m^2. The crack densities for the LC-HPC decks, however, have much lower crack density values and fall within a much tighter range of values, from 0.007 to 0.063 m/m^2. The crack densities for the three LC-HPC decks surveyed more than once increase gradually over time. The average cracking rate for these bridge decks is 0.0011 m/m^2/month. For the five control decks surveyed more than once, the crack densities increase rapidly after the first survey with an average cracking rate of 0.0137 m/m^2/month. For the decks surveyed three times, the cracking rate appears to stabilize after the second survey, indicating that it is appropriate to wait to assess cracking performance after a minimum of one year. Additional crack surveys are necessary to better assess the performance of these decks.

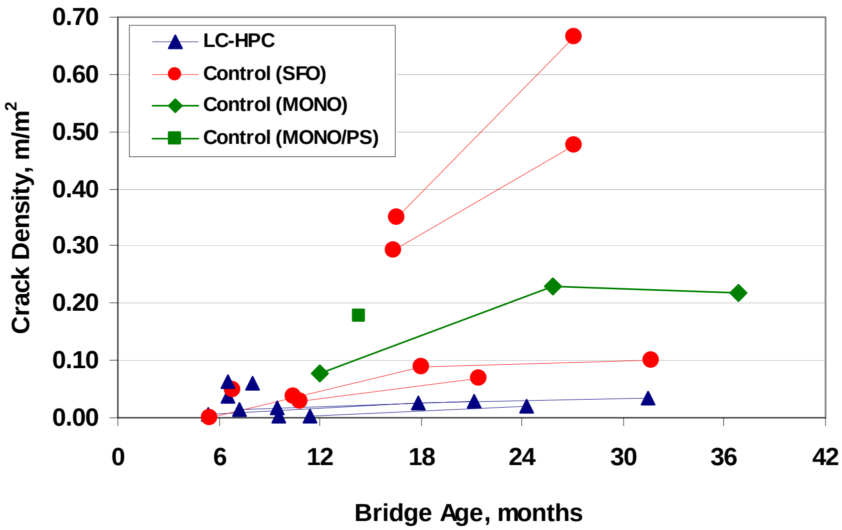


Fig. 5.43 Average Crack Density of bridge decks versus Bridge Age for LC-HPC and control decks used in this analysis. Data points connected by lines indicate the same bridge surveyed multiple times.

The individual cracking rates for the seven bridges surveyed more than once is provided by Lindquist et al. (2008). The rates are compared with average cracking rates calculated by Lindquist et al. (2005) for monolithic (0.00125 m/m^2/month) and SFO (0.00284 m/m^2/month) decks for bridges with steel girders. Lindquist et al. (2008) reported that the cracking rate for monolithic decks provides a good estimation for the LC-HPC decks, but both rates significantly underestimate the cracking rates observed for the control decks.

In this report, crack survey information for this study is compared with previous crack survey study results for monolithic decks provided by Lindquist et al. (2005). The previous study includes 14 monolithic decks cast on steel girders with 30 crack surveys performed. The crack densities Fig. 5.43 are plotted again in Fig. 5.44 along with the monolithic deck results provided by Lindquist et al. (2005). The monolithic decks from the previous study represent a much wider range of ages, but it is clear that the LC-HPC decks are performing at a level at least equal to or exceeding the best performing monolithic decks surveyed in Kansas at these very early ages.

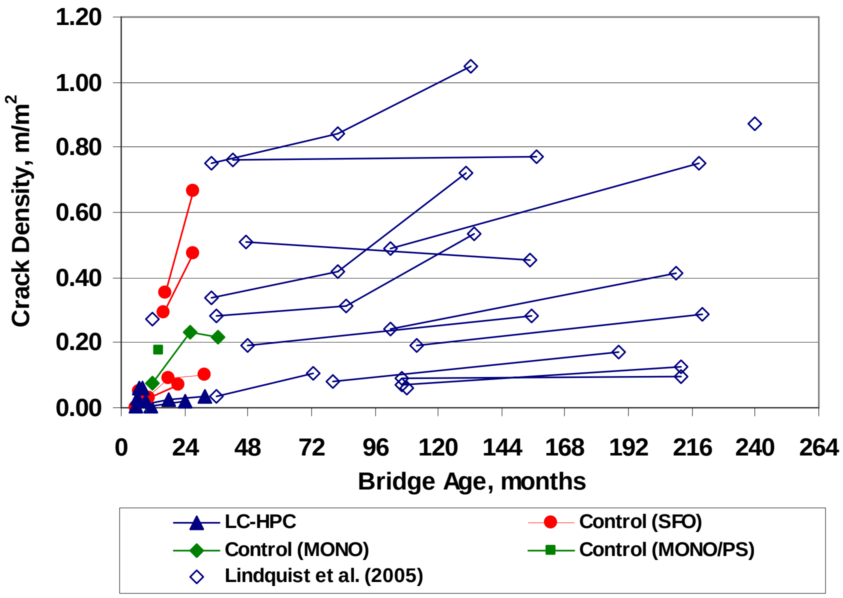


Fig. 5.44 Average Crack Density versus Bridge Age for LC-HPC and Control decks, and monolithic decks from Lindquist et al. (2005). Observations connected by lines indicate the same bridge surveyed multiple times.

5.4.2 Influence of Structure Type

Age-corrected crack density for bridge decks is shown in Fig. 5.45 as a function of superstructure type for monolithic (from previous studies) and LC-HPC bridge decks (current study), and in Fig. 5.46 for SFO (from previous studies) and SFO Control (current study) bridge decks. Four categories of superstructure type are examined: SMCC (steel beam composite continuous), WMCC (weathering steel beam composite continuous), SWCC (steel welded plate girder composite continuous), and WWCC (weathering steel welded plate girder composite continuous). For the analysis, the bridges that are SMCC and WMCC are grouped together, as are the SWCC and WWCC bridges. The single PBMC (prestressed beam continuous) bridge in this study is not included in this analysis because an age-corrected crack density cannot be determined.

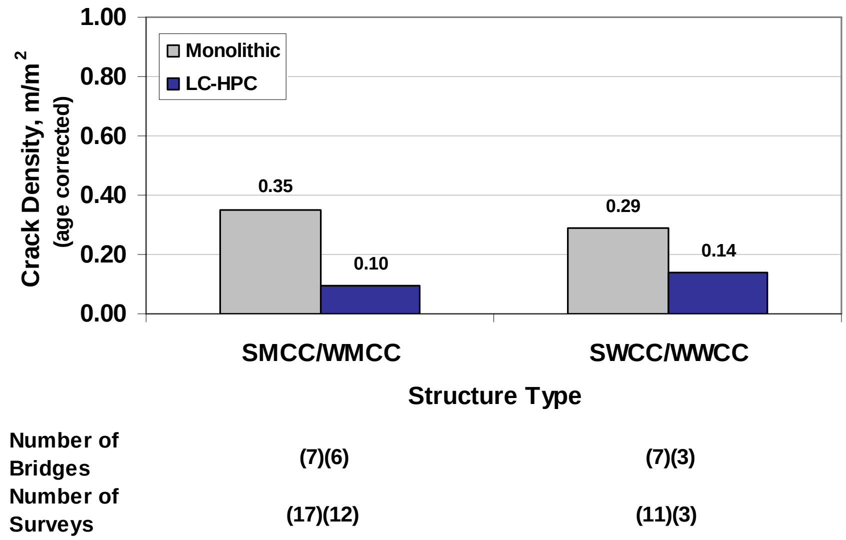


Fig. 5.45 Average Crack Density (age-corrected to 78 months) versus Structure Type for monolithic and LC-HPC decks.

All seven of the LC-HPC bridge decks are monolithic and are supported by steel girders. Of the LC-HPC bridges, two are SMCC, two are WMCC, 1 is SWCC, and 2 are WWCC. All six control bridges included in this study are supported by steel girders. Three are SMCC, two are SWCC, and one is WWCC. Of the six control decks, one is monolithic and five are two-course silica fume overlay decks. The monolithic control deck is SMCC.

For monolithic decks, SMCC/WMCC structures exhibit greater deck cracking (0.35 m/m^2) than SWCC/WWCC structures (0.29 m/m^2), whereas for LC-HPC decks, the SWCC/WWCC structures have slightly more cracking (0.14 m/m^2) than the SMCC/WMCC structures (0.10 m/m^2).

For both the SFO decks from the Lindquist et al. (2005) study and the SFO Control decks in the current study, the decks with a SMCC/WMCC structure type exhibit more cracking (0.54 and 0.38 m/m^2) than the decks with SWCC/WWCC structure type (0.45 and 0.33 m/m^2). It is also interesting to note that for both structure types, the SFO Control decks in the current study exhibit less cracking than SFO decks from the previous study.

Overall, it appears that the decks with SMCC/WMCC structure type exhibit slightly more cracking than the decks with SWCC/WWCC structure type, but this trend is not observed for the LC-HPC decks.

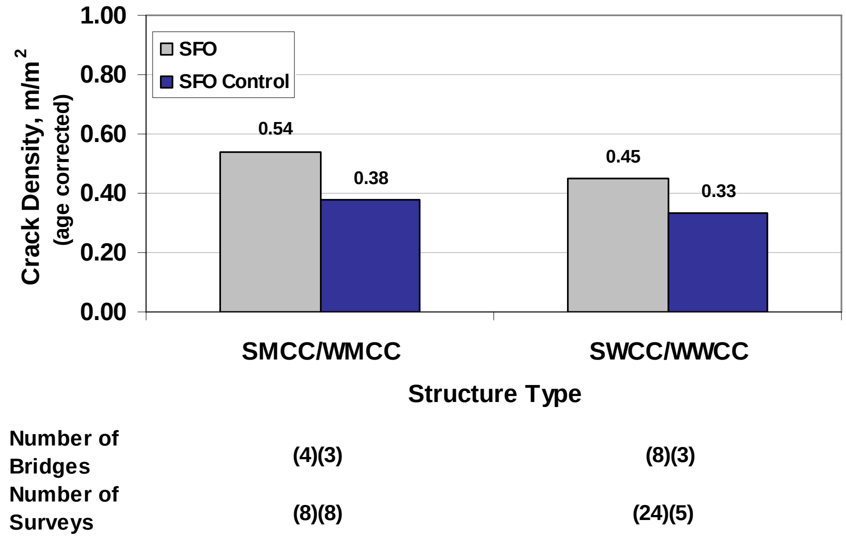


Fig. 5.46 Average Crack Density (age-corrected to 78 months) versus Structure Type for SFO (previous studies) and SFO Control (current study) decks.

5.4.3 Influence of Site Conditions

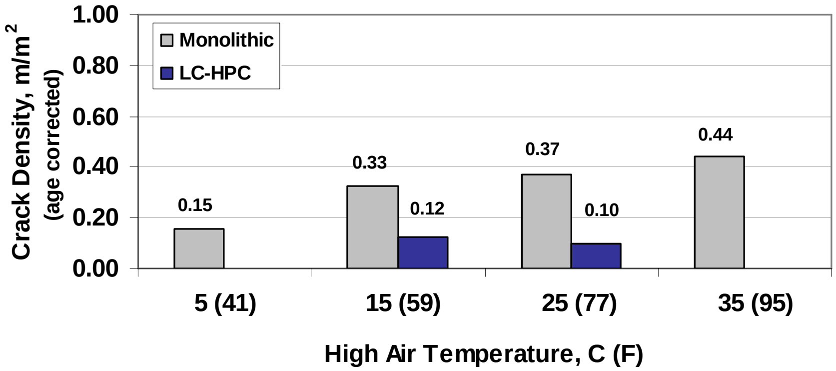
Site conditions during placement, such as air temperature and wind speed, are generally recognized as having the potential for significant impact on bridge deck cracking, particularly for thermal cracking and plastic shrinkage cracking. Air temperature, wind speed, relative humidity, and concrete temperature contribute to the rate of evaporation of water from the concrete, increasing the potential for plastic shrinkage cracking. Casting warm concrete in cool weather increases the risk for high evaporation conditions because the concrete heats the air directly above the concrete surface (dropping the relative humidity and allowing increased amounts of concrete moisture to evaporate into the warm air); the warm air is quickly replaced by cold dry air, and the cycle is continuously repeated. Historically in Kansas, factors influencing the evaporation rate, such as concrete temperature, wind speed, and relative humidity, were not regularly recorded for bridge deck construction. Currently, these parameters are recorded, although the records are not always complete.

While this analysis does not include all of the environmental conditions and materials parameters affecting cracking, the influences of three parameters are analyzed in this preliminary study, including maximum air temperature, daily air temperature range, and concrete temperature. Maximum air temperature and daily air temperature range were selected because Lindquist et al. (2005) reported them as affecting cracking for monolithic decks. This study represents the first Kansas crack survey information containing concrete temperature.

5.4.3.1 High Air Temperature

Average (age-corrected) crack density is shown as a function of the high air temperature on the day of placement in Fig. 5.47 for monolithic and LC-HPC bridge decks. The daily high temperature ranges from 6° to 36°C (43° to 97°F) for monolithic decks and from 16° to 30°C (61° to 86°F) for LC-HPC decks. The daily high air temperature categories range from 5° to 35°C (41° to 95°F). Each range category indicates the midpoint of a 10°C (18°F) temperature range. For example, 5°C (41°F) includes the bridges cast on days with high temperatures ranging from 0° to 10°C (32° to 50°F). The monolithic category includes the non-LC-HPC monolithic decks from the previous study. The crack density for the LC-HPC decks is lower than for the monolithic decks for each temperature category.

For monolithic decks, cracking increases from 0.15 to 0.44 m/m^2 as the high air temperature during the day of placement increases from 5° to 35°C (41° to 95°F), which is statistically significant at $\alpha = 0.17$ (83%). In contrast and contrary to expectations, the preliminary data for LC-HPC decks indicates a decrease in cracking with an increase in high air temperature from 15° to 25°C (59° to 77°F).



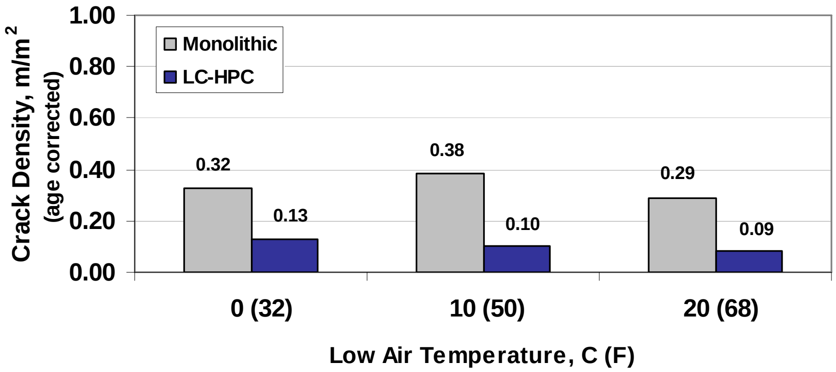
Number of Placements	(4)	(15)(5)	(9)(4)	(4)
Number of Surveys	(8)	(31)(8)	(17)(7)	(9)

Fig. 5.47 Average Crack Density (age-corrected to 78 months) versus High Air Temperature monolithic and LC-HPC bridge decks.

5.4.3.2 Low Air Temperature

Average (age-corrected) crack density is shown as a function of the low air temperature on the day of placement in Fig. 5.48 for monolithic and LC-HPC bridge decks. The low daily temperature ranges from –3° to 23°C (26° to 74°F) for monolithic decks and from 2° to 16°C (35° to 60°F) for LC-HPC decks. The daily low air temperature categories range from 0° to 20°C (32° to 68°F). Each range category indicates the midpoint of a 10°C (18°F) temperature range. For example, 10°C (50°F) includes the bridges cast on days with low air temperatures ranging from 5.1° to 15°C (41° to 59°F). The monolithic category includes the non-LC-HPC monolithic decks from the previous study. The crack density for the LC-HPC decks is lower than for the monolithic decks for each temperature category.

For monolithic decks, the low air temperature on the day of placement appears to have little effect on the cracking. The crack densities for the low air temperatures of 0°, 10°, and 20°C (32°, 50°, and 68°F) are 0.32, 0.38, and 0.29 m/m^2, respectively. There are no statistically significant differences between any of the categories. For LC-HPC decks, cracking decreases from 0.13 to 0.09 m/m^2 as the low air temperature during the day of placement increases from 0° to 20°C (32° to 68°F). A t-test cannot be performed for this difference because there is only one bridge deck placement at 20°C (68°F). Cracking decreases from 0.13 to 0.10 m/m^2 as the low air temperature increases from 0° to 10°C (32° to 50°F), statistically significant at $\alpha = 0.16$ (84%).

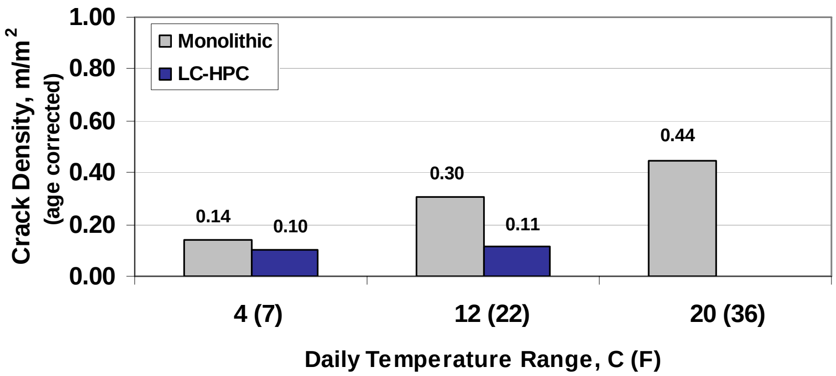


Number of Placements	(17)(4)	(10)(4)	(5)(1)
Number of Surveys	(35)(6)	(20)(7)	(10)(2)

Fig. 5.48 Average Crack Density (age-corrected to 78 months) versus Low Air Temperature monolithic and LC-HPC bridge decks.

5.4.3.3 Daily Air Temperature Range

Average (age-corrected) crack density is shown as a function of the air temperature range on the day of placement in Fig. 5.49 for monolithic and LC-HPC bridge decks. The daily temperature range, calculated as the difference between high and low air temperatures on the day of placement, varies from 2.2° to 22°C (4° to 40°F) for monolithic decks and from 7° to 16°C (13° to 28°F) for LC-HPC decks. The daily air temperature categories range from 4° to 20°C (7° to 36°F). Each range category indicates the midpoint of an 8°C (14°F) temperature range. For example, 4°C (7°F) includes the bridges cast on days with air temperature ranges ranging from 0° to 8°C (0° to 14°F). The monolithic category includes the non-LC-HPC monolithic decks from the previous study. The crack density for the LC-HPC decks is lower than for the monolithic decks for each temperature category.



Number of Placements	(2)(1)	(20)(8)	(10)
Number of Surveys	(4)(2)	(42)(13)	(19)

Fig. 5.49 Average Crack Density (age-corrected to 78 months) versus Daily Temperature Range for monolithic decks and LC-HPC decks.

For monolithic decks, cracking increases from 0.14 to 0.44 m/m^2 as the air temperature range during the day of placement increases from 4° to 20°C (7° to 36°F). This difference is not statistically significant due to a large amount of scatter in the results in the 4°C (7°F) category. Cracking increases from 0.30 to 0.44 as the air temperature range increase from 12° to 20°C (22° to 36°F), but is not statistically significant. In contrast, the preliminary data for LC-HPC decks shows essentially no difference in the cracking (from 0.10 to 0.11 m/m^2) with changes in the air temperature range from 4° to 12°C (7° to 22°F).

5.4.3.4 Concrete Temperature

Initially, all deck types are considered together. The SFO decks are based on average temperature of the SFO. There does not appear to be an obvious trend in how concrete temperature affects cracking. However, because data is available for only 16 placements, data are needed on all deck types to get a better picture of this parameter.

Average crack density for all bridge deck types in the current study is shown as a function of concrete temperature in Fig. 5.50. There is no obvious trend for the concrete temperatures shown and none of the differences are statistically significant. However, decks cast with concrete temperatures below 18°C (65°F) exhibit the highest cracking, with an average crack density of 0.28 m/m^2.

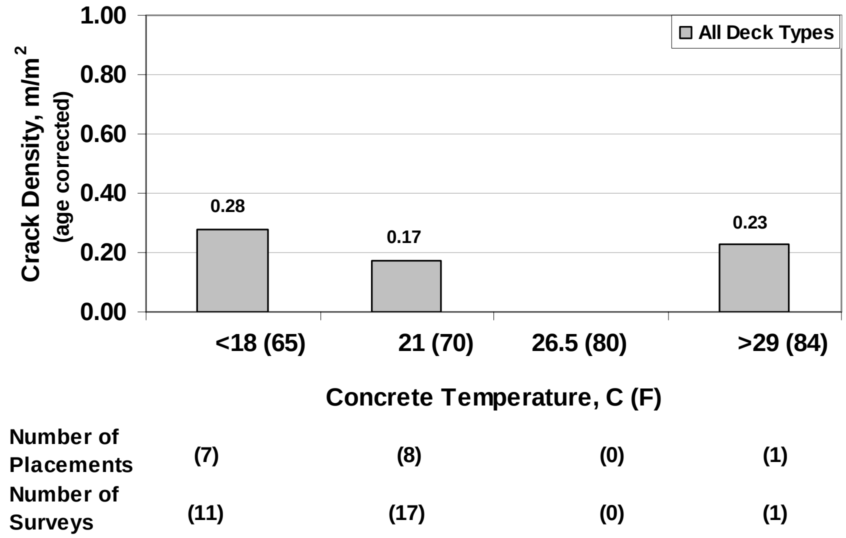


Fig. 5.50 Average Crack Density (age-corrected to 78 months) versus Concrete Temperature for all deck types.

Average crack densities for SFO and LC-HPC bridge deck types are shown in Fig. 5.51. In general, cracking increases with a decrease in the concrete temperature.

For LC-HPC decks, cracking increases from 0.10 to 0.13 m/m^2 as the concrete temperature decreases from 21°C (70°F) to 18°C (64°F), statistically significant at $\alpha = 0.04$ (96%). The LC-HPC concrete specifications limit the concrete temperature to a maximum of 24°C (75°F) and there is, therefore, no LC-HPC temperature data for the 26.5°C (80°F) and >29°C (>84°F) ranges.

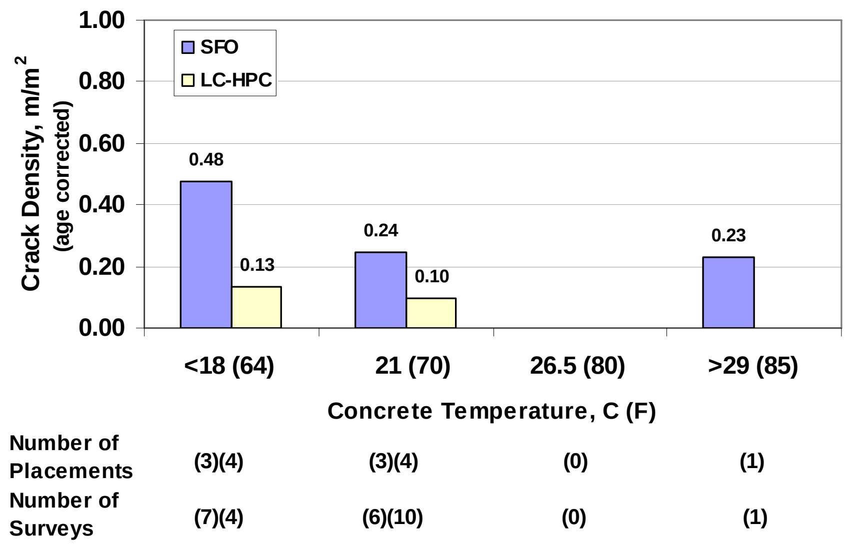


Fig. 5.51 Average Crack Density (age-corrected to 78 months) versus Concrete Temperature for SFO and LC-HPC deck types.

For the SFO decks, cracking increases from 0.23 to 0.48 m/m^2 as the concrete temperature decreases from >29°C (>85°F) to <18°C (<64°F), indicating that cracking increases as concrete temperature decreases. Since data is available for the >29°C (>84°F) category for only one placement, a statistical analysis is not appropriate. The results also show that cracking increases from 0.24 to 0.48 m/m^2 as concrete temperature decreases from 21°C (70°F) to <18°C (<64°F), statistically significant at $\alpha = 0.17$ (83%). This analysis includes 7 placements on 6 SFO bridges. Additional crack surveys on more bridges are recommended.

5.4.4 Influence of Construction Methods

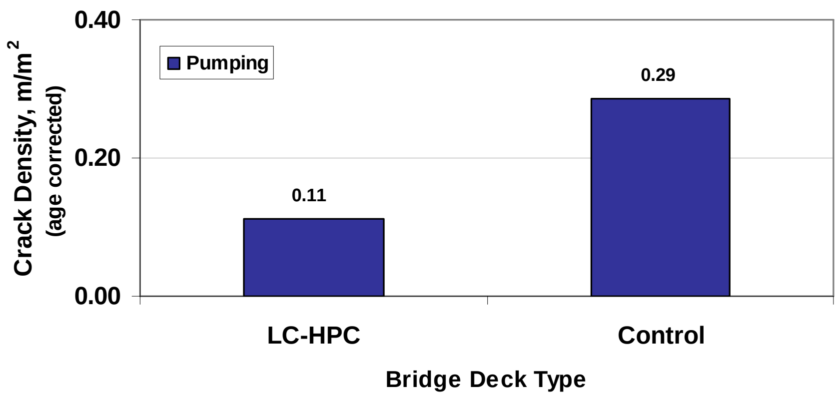
Construction methods can significantly affect the cracking tendency of concrete bridge decks, including placement method, consolidation, finishing, and curing. Increasing the concrete paste content of a mixture to ease the pumping and finishing can increase the risk for drying shrinkage cracking. Inadequate consolidation can increase settlement cracking. Overfinishing works more cement paste to the surface and can delay the initiation of curing, both of which will increase the risk for plastic shrinkage cracking. Overfinishing can also cause durability problems such as scaling. In fact, attempting to obtain a “perfect” deck finish significantly increases the risk for plastic shrinkage cracking. Controlling concrete temperatures and providing immediate wet curing can help to control thermal cracking. Methods of the protecting the concrete and the finished deck and girders during cold weather (placement and curing methods) may also significantly impact cracking on the bridge deck, if not executed properly. Overheating or removing heating without allowing the temperatures to decrease slowly can cause temperature differentials that can lead to thermal cracking. If heaters are not properly vented, carbonation can also be a problem.

In this section, different construction methods are evaluated for their potential effect on cracking. LC-HPC decks are the primary consideration, although there are a few comparisons with Control structures. Future surveys of the decks planned for this study will better quantify the effect of each construction method on cracking.

5.4.4.1 Method of Concrete Placement

All of the LC-HPC decks in this cracking analysis were placed by pumping. It is therefore not possible to compare the effects of placement method for LC-HPC construction until further crack survey information is available.

The standard method of placement for bridge decks in Kansas is pumping. Five of the seven SFO control decks (six placements) in this analysis are known to have been pumped and are included in this analysis. The monolithic prestressed-girder Control deck was pumped, but was not included in this analysis because of the difference in girder type. The method of placement for the remaining two control decks is unknown. Average age-corrected crack densities for concrete placed by pumping are shown in Fig. 5.52. The average age-corrected crack density for the LC-HPC decks placed by pumping is 0.11 m/m^2, whereas the crack density for the Control decks placed by pumping is 0.29 m/m^2, statistically significant at $\alpha = 0.01$ (99%). The comparison of LC-HPC and Control decks placed by pumping indicates that the LC-HPC decks have lower cracking than the Control structures placed with the same placement method. Further analysis of the placement method is recommended including various types of placement methods for the LC-HPC and Control decks.



	LC-HPC	Control
Number of Placements	(9)	(6)
Number of Surveys	(15)	(12)

Fig. 5.52 Average Crack Density (age-corrected to 78 months) versus Bridge Deck Type for concrete placed by pump.

5.4.4.2 Time to Burlap Placement

The average time to burlap placement is a reflection of how well the contractor adhered to the specification requirement that burlap be placed in less than 10 minutes. Only two of the nine placements included in this analysis had average time to burlap placements that met the specifications. Five of the nine placements had average placement times of less than 15 minutes, and one of the placements had an average time of greater than 20 minutes (38 minutes).

The time categories are less than 10 minutes (meeting specifications), greater than 20 minutes, and two categories (12.5 and 17.5) representing the midpoint of 5-minute time periods (10 to 15, and 15.1 to 20 minutes, respectively). Average age-corrected crack densities for various burlap placement time categories are shown in Fig. 5.53. Contrary to expectations, cracking decreases from 0.12 to 0.09 m/m^2 as the average time to burlap placement increase from less than 10 minutes to greater than 20 minutes, although none of the differences are statistically significant.

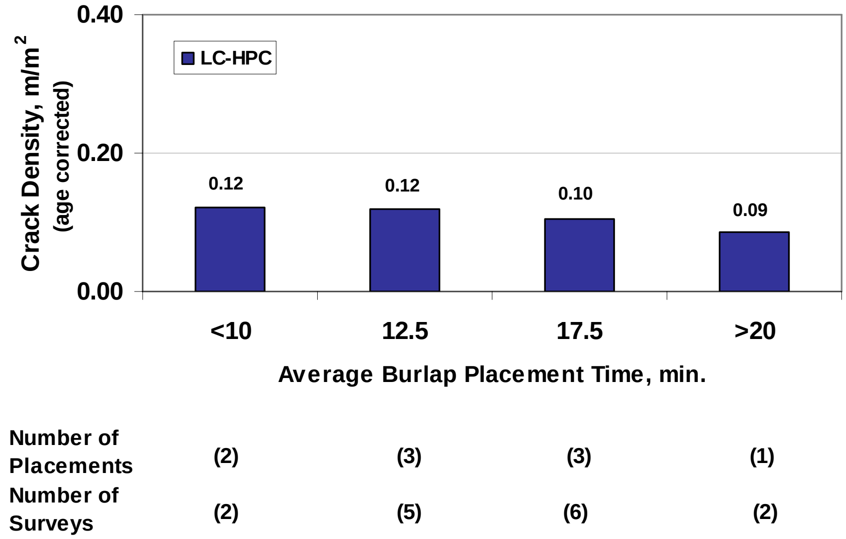


Fig. 5.53 Average Crack Density (age-corrected to 78 months) versus Average Burlap Placement Time for LC-HPC decks.

Because this analysis was performed on a small database of crack survey results, an additional analysis examining the effect of evaporation rate for each of these nine placements was also performed.

Average age-corrected crack densities for each of the nine LC-HPC placements are shown versus the maximum evaporation rate recorded during the placement in Fig. 5.54. The data was separated into three categories based on the average time to burlap placement. The categories include average time to burlap placements of less than 10 minutes (meeting specifications), 10 to 20 minutes, and greater than 20 minutes. For the two placements with average burlap placement times less than 10 minutes, there is an increase in cracking from 0.09 to 0.15 m/m^2 that correlates with an increase in the evaporation rate from 0.03 to 0.062 $lb/ft^2/hr$. However, for the six placements that have an average burlap placement time between 10 and 20 minutes, there is no apparent correlation of crack density with evaporation rate. Overall, there does not appear to be an obvious trend within the data and obtaining additional crack survey data is recommended.

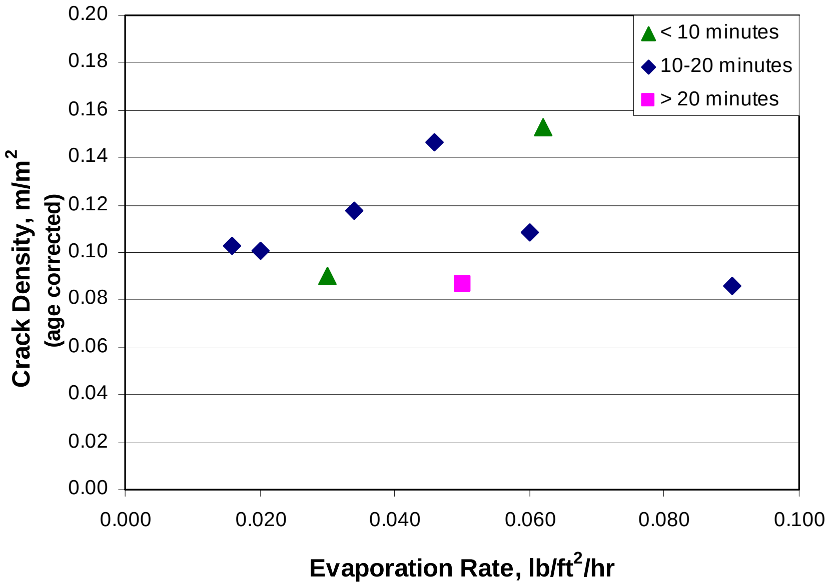


Fig. 5.54 Average Crack Density (age-corrected to 78 months) versus Evaporation Rate for LC-HPC decks with average burlap placement times of less than 10 minutes, 10-20 minutes, and greater than 20 minutes.

5.4.5 Influence of Bridge Contractor

In addition to the many materials, construction, and design variables that influence cracking on a bridge deck, the bridge contractor ultimately determines the quality of the bridge deck. Cheng and Johnston (1985) state that under identical circumstances, "different contractors produce decks of widely different qualities." Lindquist et al. (2005) stated that because the contractor plays a significant role in the overall performance of a bridge deck, a comprehensive solution to bridge deck cracking may require strict provisions for the selection of the contractor.

In the balance of this section, two parameters related to the contractor are examined. First, the average crack density for monolithic and LC-HPC decks constructed by various contractors is examined directly. Secondly, the effect of contractor experience with LC-HPC construction on cracking performance is examined.

5.4.5.1 Contractor

Average crack densities (age-corrected to 78 months) for monolithic decks from the previous studies, and for LC-HPC decks alone, are shown as a function of contractor in Fig. 5.55. The contractors identified as A through D are identified in Appendix E. For the two monolithic decks constructed by Contractor A (from previous studies), because the crack densities were low, linear extrapolation was used to estimate the crack density at a deck age of 78 months based on data taken at 106 and 212 months. For the one monolithic deck constructed by Contractor B, linear interpolation was used to estimate the crack density at a deck age of 78 months based on data taken at 34 and 82 months. The current LC-HPC decks are age-corrected.

The decks constructed by Contractor B had the highest average crack density for the one monolithic deck (0.84 m/m^2) and the eight LC-HPC deck placements (0.11 m/m^2). The decks constructed by Contractor A had the lowest average crack density for two monolithic deck placements (0.07 m/m^2) and one LC-HPC deck placement (0.09 m/m^2).

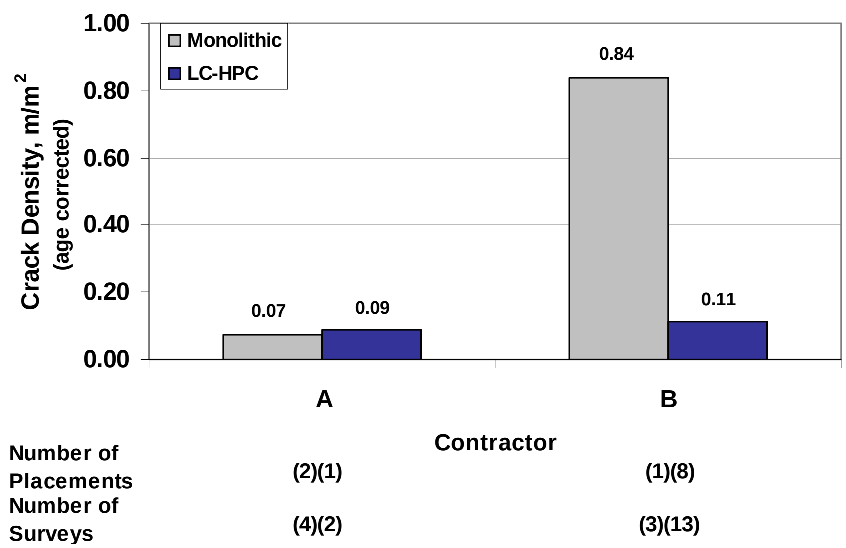


Fig. 5.55 Average Crack Density (age-corrected to 78 months) versus Contractor for monolithic (non-LC-HPC) and LC-HPC bridge decks.

Average crack densities for SFO Control decks (steel girders) and LC-HPC decks in this study, are shown as a function of contractor in Fig. 5.56. In this analysis, Contractor A has completed one LC-HPC bridge deck, Contractor B has completed six LC-HPC and four Control decks (the latter in six placements), Contractor C has completed two Control bridge decks, and Contractor D has completed one Control deck.

For the LC-HPC decks, Contractor A has the lowest average crack density of 0.09 m/m^2, representing one deck. Contractor B has a higher average crack density of 0.11 m/m^2, representing six LC-HPC decks (eight placements). All six of the bridge decks constructed by Contractor B had the same concrete supplier and several of the decks caused significant challenges during construction. Because only two contractors are represented in the LC-HPC crack survey results, crack surveys of additional LC-HPC bridges will prove useful.

For the Control decks, Contractor C had the highest average crack density, at 0.67 m/m^2, representing one bridge deck. Contractor B had an average crack density for four Control bridge decks (six placements) of 0.29 m/m^2, and Contractor D had the lowest average crack density of 0.24 m/m^2, representing one Control bridge deck (steel girder), which also happened to be monolithic, possibly contributing to the lower crack density.

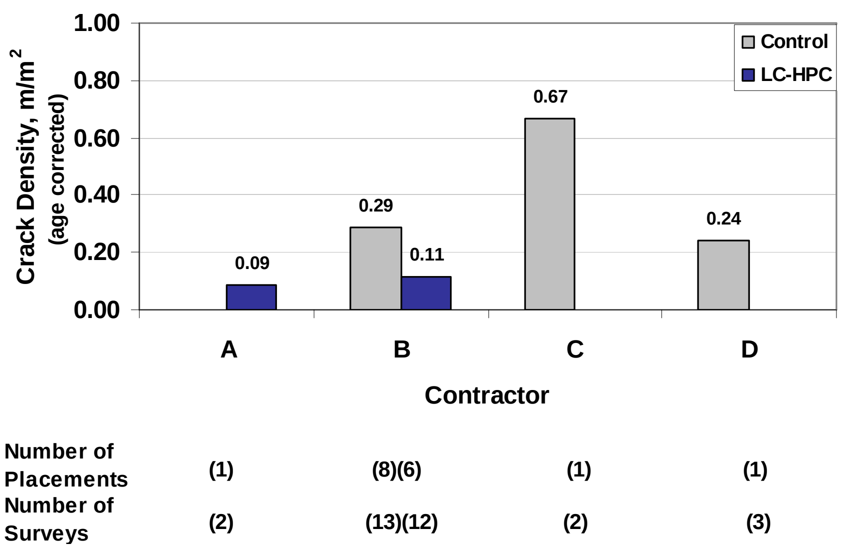


Fig. 5.56 Average Crack Density (age-corrected to 78 months) versus Contractor for Control and LC-HPC decks for bridges with steel girders in this study.

5.4.5.2 Contractor Experience

The average crack density as a function of the number of experiences that Contractor B had with placing or attempting to place LC-HPC is presented in Fig. 5.57. The experiences include eight bridge deck placements and four qualification slab placements (three were successfully completed), but do not include qualification batches. The qualification slab placements do not provide crack density data. Experiences 3 and 4 are two placements cast in the fall and were the two first LC-HPC bridge placements (one bridge) cast in Kansas. Experience 6 is in the same contract as 3 and 4, and was also cast in the fall, approximately a year later. Experiences 8 through 12 were part of the same contract with several of the bridges cast under cold weather placement and curing conditions. Because so many parameters influence the results for each experience, it is difficult to draw any conclusions for contractor experience.

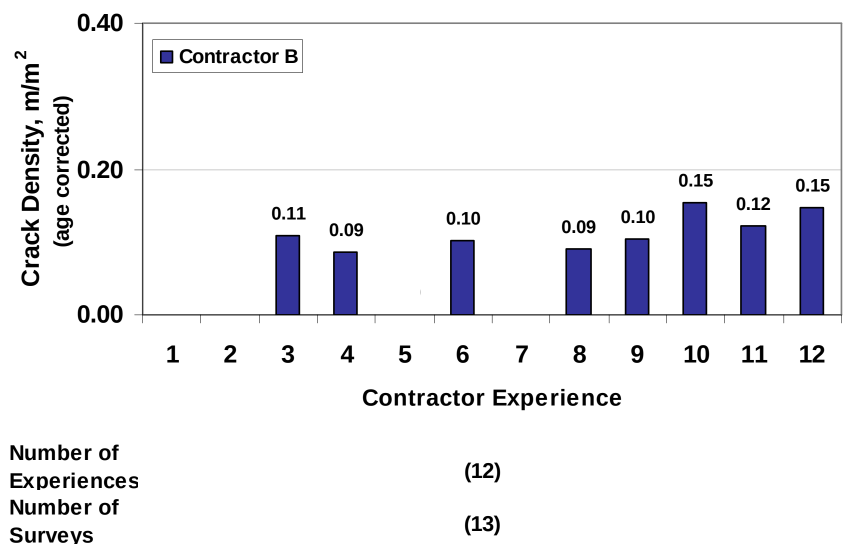


Fig. 5.57 Average Crack Density (age-corrected to 78 months) versus Contractor Experience for Contractor B.

Chapter 6

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1 SUMMARY

The problem of bridge deck cracking has been studied for many years, and the causes of cracking are well documented. There remain, however, many questions about how to successfully implement techniques to reduce cracking in the field. This study seeks to answer some of these questions by focusing on the development and construction of Low-Cracking High-Performance Concrete (LC-HPC) bridge decks. The study is divided into three parts covering (1) an evaluation of the chloride penetration into concrete using long-term salt-ponding tests, (2) a comprehensive discussion of specifications for LC-HPC construction and standard practices in Kansas, and (3) the description of the construction and the preliminary evaluation of LC-HPC and control bridge decks in Kansas.

Preventing cracking on bridge decks is of primary importance in protecting bridge deck reinforcing steel from corrosion and the decks from freeze-thaw damage, because cracks provide a direct pathway for deicing chemicals to penetrate the concrete. The prevention of chloride ingress through solid concrete is also important. The first portion of the study involves evaluating the effect of paste content, curing period, water-cement ratio, cement type, mineral admixtures, and a shrinkage reducing admixture on the chloride penetration into solid concrete. Standard DOT bridge deck mixtures are included in the study. Mixtures are evaluated by exposing specimens to salt ponding using "Resistance of Concrete to Chloride Ion Penetration," AASHTO T 259, performing precision sampling with a lathe, and testing samples for chloride content. Careful consideration is given to the aggregate gradations, cohesiveness, workability, finishability, and apparent constructability prior to casting the specimens. All of the mixtures in this study, except for the standard DOT mixtures, have an optimized aggregate gradation, a target air content of 8%, a target slump of either 75±13 mm (3±½ in.) or 75±25 mm (3±1 in.), and a water-cement ratio between 0.41 and 0.45.

The evaluation of chloride ingress into concrete includes a total of 33 individual concrete batches and 123 specimens. The results are presented in seven test programs. Program 1 evaluates the effect of paste content on chloride ingress. Mixtures with paste contents ranging from 20.5% to 24.2% are tested. Some mixtures contain mineral admixtures, including 60% replacement with Grade 120 GGBFS and 6% replacement with silica fume. Program 2 examines the effect of curing period, ranging from 7 to 28 days. The specimens were cast with Type I/II and coarse ground Type II cements. Water-cement ratio is evaluated in Program 3 using two different approaches. One approach is to vary the paste content while varying the *w/c* ratio (from 0.41 to 0.45), maintaining a constant cement content of 317 kg/m^3 (535 lb/yd^3), similar to the construction practice of *retempering*. The other approach is to maintain a constant paste content and vary the *w/c* ratio (from 0.36 to 0.42), isolating the effect of *w/c* ratio alone. Program 4 evaluates Type I/II and Type II portland cement. Coarse and medium ground Type II cements were used with Blaine fineness values of 3060 cm^3/g and 3351 cm^3/g, respectively. Program 5 evaluates the effect of mineral admixtures as partial replacements for Type I/II portland cement on chloride ingress, including silica fume, and Grades 100 and Grade 120 GGBFS. The effect of a shrinkage reducing admixture (SRA) on chloride ingress is evaluated in Program 6. The final test program, Program 7, compares LC-HPC with two DOT mixtures – one a standard subdeck mixture used in Kansas, and the other a modification of a bridge deck mixture historically used in Missouri.

The second portion of this study describes the specifications for the LC-HPC and Control bridge decks in Kansas. The focus is on the construction methods, including the evolution of the specifications over time, with an overview of the materials.

The third portion of this study details the development and construction of 14 LC-HPC and 12 Control bridge decks built in Kansas. The design details, construction experiences, and lessons learned for the LC-HPC bridge decks are described in detail, and an overview of the materials is presented; the design and construction data for each Control deck is provided; and initial crack survey results are evaluated for various construction-related parameters. A complete discussion of the LC-HPC material development and experiences is presented by Lindquist et al. (2008).

6.2 CONCLUSIONS

The following observations and conclusions are based on the results, analyses, and construction experiences presented in this report.

6.2.1 Chloride Ingress

1. For mixtures containing 100% portland cement, decreases in paste content result in an increase in chloride ingress.

2. The presence of mineral admixtures (silica fume or GGBFS) generally reduces chloride ingress compared to mixtures containing 100% portland cement. The permeability of these mixtures is less sensitive to minor changes in paste content at low paste levels.

3. Longer curing periods decrease chloride ingress.

4. For concrete containing Type I/II cement, an increase in the *w/c* ratio (and paste content) due to the addition of water to the mix, similar to the construction practice of *retempering*, results in no significant effect in chloride ingress. For medium ground Type II cement, an increase in the *w/c* ratio (and paste content) results in an increase in chloride ingress.

5. For a constant paste content, an increase in the *w/c* ratio results in a slight increase in chloride ingress.

6. Concrete containing coarse ground Type II cement (Blaine fineness = 3060 cm^3/g) or medium ground Type II cement (Blaine fineness = 3351 cm^3/g) exhibits greater chloride ingress than concrete containing Type I/II cement.

7. Partial replacement of portland cement with Grade 100 or Grade 120 GGBFS reduces chloride ingress.

8. Partial replacement of portland cement with Grade 100 GGBFS is more effective at reducing chloride ingress than Grade 120 GGBFS.

9. Cement replacement levels of 30% and 60% (by volume) using Grade 120 GGBFS provides a similar benefit in limiting chloride ingress.

10. An increase in the replacement level from 3% to 6% (by volume) of silica fume provides additional protection from chloride ingress.

11. Ternary mixtures containing 60% Grade 100 GGBFS and 6% silica fume (by volume) exhibit less chloride ingress than binary mixtures containing 60% Grade 100 GGBFS.

12. The addition of 1% or 2% shrinkage reducing admixture (SRA) (by weight of cement) to concrete mixtures (replacing an equal weight of water in the mix) may result in slight decreases in chloride ingress, although the current results are inconclusive. Before these mixtures are implemented, careful consideration must be given to interaction with other chemical admixtures, mixing procedures, and placement techniques to ensure a stable and reproducible air-void system in the bridge deck.

13. The KDOT standard subdeck mixture exhibits greater chloride penetration than LC-HPC mixtures with a cement content of 318 kg/m^3 (535 lb/yd^3) and *w/c* ratios of 0.45 or 0.42.

6.2.2 LC-HPC Construction Specifications and Construction Experiences

1. Successful LC-HPC bridge deck construction is repeatable.

Placement

2. Timely delivery of concrete that meets specifications is critical to the successful completion of an LC-HPC placement. Back-orders can cause delays at the end of a placement and lengthen periods during which the concrete is left exposed to drying conditions.

3. A raised ramp is helpful for concrete trucks to discharge lower slump concrete into the pump hoppers.

4. LC-HPC can be successfully placed using conveyor belts, concrete buckets, and concrete pumps.

5. Conveyors are efficient for placing concrete, but the concrete drop needs to be limited to limit air loss.

6. Manufactured sand can have a negative impact on the pumpability of low-paste content LC-HPC mixtures.

7. Pumping difficulties significantly disrupt bridge construction and cause negative attitudes on the part of contractors, materials suppliers, and testing crews, which may have negative consequences for future LC-HPC projects. If the contractor intends to place the concrete by pump, the pumping should be demonstrated using the same equipment and the same mixture (meeting all the concrete specifications) used on the deck, prior to the day of deck construction to ensure that the mix will pump.

8. Coarse aggregate particles remain close to the deck surface when a single-drum roller screed is used for strike-off.

9. Consolidation using gang vibration equipment provides more thorough consolidation of the concrete than hand vibration.

10. Prefilling the final end wall and diaphragms can help to minimize delays at the end of a placement. Two pumps or conveyors are helpful in prefilling the final abutment, for placements requiring the pump to be moved, and for wide deck placements to avoid delays in finishing and burlap placement. Prefilling the final abutment may also be completed directly from trucks.

11. Concrete material cost is a primary concern for the contractor, and they will tolerate delays at the end of a placement to avoid purchasing more concrete than needed. This is a common occurrence.

Finishing

12. Machine mounted fogging equipment rarely works. It usually deposits water on the concrete surface during finishing.

13. Some minor surface imperfections on the deck are acceptable.

14. Grinding is not necessary for every deck.

15. A surface finish applied with a broom, such as for a sidewalk, is not significantly affected by the careful application of wet burlap.

Burlap/Curing

16. Burlap placement for LC-HPC is labor intensive and requires planning prior to placement.

17. Placing burlap in single layers ensures overlap between burlap pieces and allows layers to be staggered, also reducing the risk that concrete would be exposed or dry out.

18. All concrete should be covered with wet burlap during delays. Hand held fogging equipment may also be used as a backup during delays.

19. Burlap can be kept wet with spray hoses or sprinklers. If needed, holes should be drilled in the forms to allow excess water to drain.

20. For superelevated decks, soaker hose placement on the highest point on the deck is important to ensure that the deck is kept wet throughout the curing period.

21. Additional curing time required by the newest version of the specifications for cold weather curing must be actively managed and recorded. Not doing can result in insufficient curing.

Temperature

22. Girder temperatures are not uniform at the locations where concrete has not been placed and are not necessarily equivalent to the ambient air temperature.

23. Portions of girders in contact with placed concrete have more uniform temperature through their depth than the portions of the same girder not in contact with the concrete.

Communication/Inspection

24. Clear and consistent communication between the contractor, owner, and testing personnel is vital for successful completion of LC-HPC decks.

25. "Buy-in" and active enforcement of the specifications on the part of the Owner's engineer and head inspector have great influence over the success of the project. Clear written and verbal communication is necessary for the successful completion of an LC-HPC deck. Significant effort may be required in assisting the concrete supplier, contractor, and the Owner's engineer.

26. Active and aggressive pressure from contractors can significantly influence an owner to accept materials and methods that do not meet specifications.

27. Rejecting out-of-specification concrete not only keeps substandard concrete out of the deck, but also helps to maintain tighter control of concrete properties throughout the project and sends a message to the contractor that the specifications must be followed.

28. A plan for concrete testing, how to handle trucks that do not meet specifications, and requirements for testing of subsequent trucks should be established early in the project and reviewed with the testing crew just prior to the start of placement.

29. Maintaining open lines of communication with the contractor, even when difficult, especially when unforeseen complications arise, is vital to the successful implementation of the project.

30. Each job can affect future jobs. The contractor’s perceived experience with LC-HPC can impact future projects. Communication between contractors regarding previous LC-HPC experiences can influence attitudes toward future projects.

31. Producing a qualification batch shortly before producing the qualification slab (less than 35 days prior) may cause problems in developing a concrete mixture that fully meets the specifications and can be placed in the manner desired by the contractor.

32. Prequalification and the use of more than one mixture for the qualification slab may not provide the supplier adequate experience during the placement to produce multiple and successive batches of the LC-HPC prior to deck placement.

33. Because it is important that the concrete surface does not dry out during the time between the removal of the wet burlap and the application of the curing membrane, inspection at this time can support the timely application of the membrane and also provide a record of inadequate curing if the concrete is dry when the burlap is removed.

6.2.3 Preliminary Evaluation of LC-HPC and Control Bridge Decks

1. LC-HPC decks crack less than Control structures.

2. LC-HPC decks crack less than monolithic structures from previous studies.

3. Additional crack surveys will be necessary to quantify how construction methods affect cracking of LC-HPC bridge decks.

6.3 RECOMMENDATIONS

Based on the observations and conclusions in this report, the following recommendations are first made to improve long-term salt ponding testing, and to perform additional permeability tests. Second, recommendations are made in regard to specifications and construction procedures to limit cracking and chloride ingress in bridge decks.

Improve Chloride Ingress Testing:

Long-term salt ponding testing specimens should be epoxy-coated on the vertical surface to limit the effects of drying and wicking.

Long-term salt ponding testing specimens should be cored immediately after deponding. If they will be precision-sampled after coring, the cored specimens should be sealed in plastic bags and frozen until sampling is preformed.

Additional Permeability Testing:

Additional long-term ponding tests of concrete containing SRA for chloride ingress are recommended, including 1% SRA and lower dosage rates, curing periods of 7 and 14 days, and mixtures containing both SRA and silica fume for improved cohesion. Companion tests for free shrinkage and strength are also recommended.

New long-term ponding tests of LC-HPC concrete containing low replacement levels of silica fume and tests with SRA and silica fume together are recommended.

New long-term ponding testing of LC-HPC concrete containing granite to evaluate chloride ingress for concrete containing aggregates used in the field is recommended. Because granite is very hard and difficult to machine, a new precision sampling technique will be necessary, possibly using diamond tool bits for the lathe or on a grinder.

Construction and Specification Items:

Quality Control Plan (QCP). Per the specifications, the Engineer should require submittal of a Quality Control Plan (QCP) prior to placing LC-HPC. This has not been done for any LC-HPC placement to date.

Communication. KU personnel and DOT supervisors should always maintain clear lines of communication with the contractor, supplier, and testing personnel.

Aggregates. Manufactured sand is not recommended for LC-HPC construction.

Concrete Testing. Testing crews should have duplicates of all testing equipment, including but not limited to slump cones, air content testing equipment, and thermometers.

Concrete Testing. KU personnel and DOT supervisors should work with each testing crew so they understand the importance of the new procedures and are on-board with enforcing the specifications.

Qualification Batch. Per the specifications, the qualification batch should be produced at least 35 days prior to placement of the bridge deck. All concrete properties must meet specifications, including concrete temperature. Consider requiring two qualification batches, both meeting all specifications, and produced in series with similar wait-times between truckloads as anticipated for the bridge deck placement.

Qualification Slab. One mix design should be used during the qualification slab to give the concrete supplier adequate experience in producing multiple and successive batches of the concrete before the deck placement.

Qualification Slab. Only concrete that meets specifications should be placed in the qualification slab.

Qualification Slab. Minimum requirements for the placement of burlap should be established.

Conveyor Belts. The elevation of the concrete drop should be minimized for placements completed using conveyor belts.

Consolidation. The engineer should check for positive control of vibrators in the form of a timed light, buzzer or automatic control or other approved method as required by KDOT specifications. To date, this has not been done for a LC-HPC placement.

Fogging. To ensure the equipment is available and functional, the Contractor should demonstrate the proper use of hand-held fogging equipment prior to and on the day of placement, prior to placing LC-HPC.

Minimize Evaporation During Delays. During delays expected to exceed 10 minutes, cover all concrete (placed or finished) with wet burlap.

Backordering Concrete. Consider allowing the DOT to pay for the direct cost of the leftover concrete at the end of a placement to avoid the need to backorder concrete and delay completion of a placement.

Heating Girders. Positive temperature control and adequate ventilation should be provided if girders are heated during curing.

Cold Weather Curing. Additional curing time required by the new specifications for cold weather curing must be actively managed and recorded. Not doing so can result in insufficient curing for LC-HPC placements.

Inspection Report. Per the specifications, the Engineer should collect the inspection records for curing from the Contractor. This has not been done for any LC-HPC placement to date.

Form Removal. Records related to the date of the removal of deck forms should be submitted to the engineer.

Delays between Placements. If more than 6 months has passed since the previous LC-HPC placement, then a meeting should be held between the contractor, DOT personnel, and the concrete supplier to review the methods and discuss the plan for construction prior to LC-HPC placement.

REFERENCES

AASHTO T 259–02, (2002). “Standard Method of Test for Resistance of Concrete to Chloride Ion Penetration,” *Standard Specifications for Transportation Materials and Methods of Sampling and Testing - Part II Tests*, American Association of State Highway and Transportation Officials, Washington, D.C., pp. T 259-1–T 259-3.

AASHTO T 259–80, (1980). “Standard Method of Test for Resistance of Concrete to Chloride Ion Penetration,” *Standard Specifications for Transportation Materials and Methods of Sampling and Testing - Part II Tests*, American Association of State Highway and Transportation Officials, Washington, D.C., pp. 923–924.

AASHTO T 260–97, (2001). “Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials,” *Standard Specifications for Transportation Materials and Methods of Sampling and Testing, American Association of State Highway and Transportation Officials*, Washington, D.C., pp. T 260-1–T 260-15.

AASHTO T 277–07, (2007). “Standard Method of Test for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration,” *Standard Specifications for Transportation Materials and Methods of Sampling and Testing - Part II Tests*, American Association of State Highway and Transportation Officials, Washington D.C., pp. T 277-1–T 277-12.

ACI Committee 308, (1997). *Standard Practice for Curing Concrete, ACI 308-92*, American Concrete Institute, Farmington Hills, Michigan.

Aktan, H., Fu, G., Dekelbab, W., and Attanayaka, U., (2003). “Investigate Causes and Develop Methods to Minimize Early-Age Deck Cracking on Michigan Bridge Decks,” RC-1437, Michigan Department of Transportation, 214 pp.

ASTM C1152/C1152M, (2004). “Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete,” ASTM International, West Conshohocken, PA, 4 pp.

ASTM C1202–07, (2007). “Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration,” ASTM International, West Conshohocken, PA, 6 pp.

ASTM C1543–02, (2002). “Determining the Penetration of Chloride Ion into Concrete by Ponding,” ASTM International, West Conshohocken, PA, 3 pp.

ASTM C1556–04, (2004). “Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion,” ASTM International, West Conshohocken, PA, 7 pp.

ASTM C1585–04, (2004). “Measurement of Rate of Absorption of Water by Hydraulic Cement Concretes,” ASTM International, West Conshohocken, PA, 6 pp.

Atkinson, A., and Nickerson, A. K., (1984). "Diffusion of Ions Through Water-Saturated Cement," *Journal of Materials Science*, Vol. 19, No. 9, pp. 3068–3078.

Babaei, K., and Purvis, R., (1995a). "Prevention of Cracks in Concrete Bridge Decks: Report on Observations of Bridge Deck Construction and Concrete Shrinkage Measurements in the Field," *Report* PA-FHWA-95-002+89-01, 28 pp.

Babaei, K., and Purvis, R., (1996). "Prevention of Cracks in Concrete Bridge Decks," *Summary Report* PA-FHWA-95-006+89-01, 30 pp.

Babaei, K., and Purvis, R. L., (1995b). "Prevention of Cracks in Concrete Bridge Decks: Report on Surveys of Existing Bridges," *Report* PA-FHWA-95-001+89-01, 100 pp.

Bentur, A., Igarashi, S. I., and Kovler, K., (2001). "Prevention of Autogenous Shrinkage in High-Strength Concrete by Internal Curing Using Wet Lightweight Aggregates," *Cement and Concrete Research*, Vol. 31, No. 11, pp. 1587–1591.

Bentz, D. P., (2007). "Internal Curing of High-Performance Blended Cement Mortars," *ACI Materials Journal*, Vol. 104, No. 4, pp. 408–414.

Bentz, D. P., Lura, P., and Roberts, J. W., (2005). "Mixture Proportioning for Internal Curing," *Concrete International*, Vol. 27, No. 2, pp. 35–40.

Bentz, D. P., and Snyder, K. A., (1999). "Protected Paste Volume in Concrete: Extension to Internal Curing Using Saturated Lightweight Fine Aggregate," *Cement and Concrete Research*, Vol. 29, No. 11, pp. 1863–1867.

Berke, N. S., and Hicks, M. C., (1996). "Predicting Times to Corrosion From Field and Laboratory Chloride Data," Techniques to Assess the Corrosion Activity of Steel Reinforced Concrete Structures, ASTM STP 1276, N. S. Berke, C. K. Nmai, and D. Whiting, eds., SAE, Warrendale, PA, USA, pp. 41–57.

Boulfiza, M., Sakai, K., Banthia, N., and Yoshida, H., (2003). "Prediction of Chloride Ions Ingress in Uncracked and Cracked Concrete," *ACI Materials Journal*, Vol. 100, No. 1, pp. 38–48.

Cheng, T. T., and Johnston, D. W., (1985). "Incidence Assessment of Transverse Cracking in Concrete Bridge Decks: Construction and Material Considerations," *Final Report* FHWA/NC/85-002, Vol. 1, North Carolina State University Department of Civil Engineering, Raleigh, NC, 232 pp.

Dakhil, F. H., Cady, P. D., and Carrier, R. E., (1975). "Cracking of Fresh Concrete as Related to Reinforcement," *ACI Journal*, Vol. 72, No. 8, pp. 421–428.

Darwin, D., Browning, J., and Lindquist, W., (2004). "Control of Cracking in Bridge Decks: Observations from the Field," *Cement, Concrete and Aggregates*, Vol. 26, No. 2, pp. 148–154.

Deshpande, S., Darwin, D., and Browning, J., (2007). "Evaluating Free Shrinkage of Concrete for Control of Cracking in Bridge Decks," *SM Report* No. 89, University of Kansas Center for Research, Inc., Lawrence, Kansas, 290 pp.

Detwiler, R. J., and Fapohunda, C. A., (1993). "A Comparison of Two Methods for Measuring the Chloride Ion Permeability of Concrete," *Cement, Concrete and Aggregates*, Vol. 15, No. 1, pp. 70–73.

Detwiler, R. J., Kjellsen, K. O., and Gjorv, O. E., (1991). “Resistance to Chloride Intrusion of Concrete Cured at Different Temperatures,” *ACI Materials Journal*, Vol. 88, No. 1, pp. 19–24.

Detwiler, R. J., Whiting, D. A., and Lagergren, E. S., (1999). “Statistical Approach to Ingress of Chloride Ions in Silica Fume Concrete for Bridge Decks,” *ACI Materials Journal*, Vol. 96, No. 6, pp. 670–675.

Ducret, J.-M., and Lebet, J.-P., (1997). “Measurements on a Composite Bridge: Effects of Concrete Hydration,” *Composite Construction in Steel and Concrete III - Proceedings of an Engineering Foundation Conference*, Irsee, Germany, pp. 211–221.

Ducret, J.-M., Lebet, J.-P., and Monney, C., (1997). “Hydration Effects and Deck Cracking During Construction of Steel-Concrete Composite Bridges,” *Recent Advances in Bridge Engineering: Evaluation, Management and Repair*, U. Meier and R. Betti, eds., Zurich, Switzerland, pp. 25–32.

Durham, S. A., Hale, W. M., and Kuss, M. L., (2005). “Innovative Test Method for Measuring the Permeability of Concrete,” *International Conference on Young Researchers' Forum*, Dundee, Scotland, United Kingdom, pp. 67–74.

Eppers, L. J., French, C. E., and Hajjar, J., (1998). “Transverse Cracking in Bridge Decks: Field Study,” *Final Report*, Minnesota Department of Transportation, St. Paul, Minnesota, 102 pp.

Fanous, F., and Wu, H., (2005). “Performance of Coated Reinforcing Bars in Cracked Bridge Decks,” *Journal of Bridge Engineering*, Vol. 10, No. 3, pp. 255–261.

FHWA High Performance Concrete Technology Delivery Team, (2005). *High Performance Concrete Structural Designer's Guide*, Federal Highway Administration, 120 pp.

French, C., Eppers, L., Le, Q., and Hajjar, J., (1999a). “Transerse Cracking in Concrete Bridge Decks,” *Transportation Research Record*, Vol. 1668, No. 1, pp. 21–29.

French, C. E., Eppers, L. J., Le, Q. T. C., and Hajjar, J. F., (1999b). “Transverse Cracking in Bridge Decks,” *Summary Report*, Minnesota Department of Transportation, St. Paul, Minnesota, 37 pp.

Frosch, R. J., Radabaugh, R. D., and Blackman, D. T., (2002). “Investigation of Transverse Bridge Deck Cracking,” *2002 Structures Congress - Performance of Structures from Research to Design*, Denver, Colorado, pp. 363–364.

Grady, J. E., (1983). “Effects of Sawed-Groove Texturing on Concrete Bridge Decks,” *Report* FHWA/NY/RR-83/108, Engineering Research and Development Bureau New York State Department of Transportation, Albany, NY, 42 pp.

Hansen, E. J., and Saouma, V. E., (1999). “Numerical Simulation of Reinforced Concrete Deterioration - Part I: Chloride Diffusion,” *ACI Materials Journal*, Vol. 96, No. 2, pp. 173–180.

Holland, T., (2005). “Silica Fume User's Manual,” *Technical Report* FHWA-IF-05-016, Federal Highway Administration, 193 pp.

Hooton, R. D., Geiker, M. R., and Bentz, E. C., (2002). "Effects of Curing on Chloride Ingress and Implications on Service Life," *ACI Materials Journal*, Vol. 99, No. 2, pp. 201–206.

Issa, M. A., (1999). "Investigation of Cracking in Concrete Bridge Decks at Early Ages," *Journal of Bridge Engineering*, Vol. 4, No. 2, pp. 116–124.

Ji, J., Darwin, D., and Browning, J., (2005). "Corrosion Resistance of Duplex Stainless Steels and MMFX Microcomposite Steel for Reinforced Concrete Bridge Decks," *SM Report* No. 80, University of Kansas Center for Research, Inc., Lawrence, KS, 456 pp.

Jones, D. A., (1996). *Principles and Prevention of Corrosion*, 2nd ed., Prentice Hall, Upper Saddle River, NJ, 572 pp.

Kansas Department of Transportation, (1990a). "Section 151.09(e) Vibrators for Bridge Decks," *Standard Specifications for State Road and Bridge Construction*, Topeka, Kansas, pp. 108.

Kansas Department of Transportation, (1990b). "Section 701.03(e) Handling and Placing Concrete," *Standard Specifications for State Road and Bridge Construction*, Topeka, Kansas, pp. 382–383.

Kansas Department of Transportation, (2007a). "Section 154.2(d) Vibrators for Bridge Decks," *Standard Specifications for State Road and Bridge Construction*, Topeka, Kansas.

Kansas Department of Transportation, (2007b). "Section 710.3(b) Handling and Placing Concrete," *Standard Specifications for State Road and Bridge Construction*, Topeka, Kansas.

Kassir, M. K., and Ghosn, M., (2002). "Chloride-Induced Corrosion of Reinforced Concrete Bridge Decks," *Cement and Concrete Research*, Vol. 32, No. 1, pp. 139–143.

Kirkpatrick, T. J., Weyers, R. E., Anderson-Cook, C. M., and Sprinkel, M. M., (2002). "Probabilistic Model for the Chloride-Induced Corrosion Service Life of Bridge Decks," *Cement and Concrete Research*, Vol. 32, No. 12, pp. 1943-1960.

Kovler, K., Souslikov, A., and Bentur, A., (2004). "Pre-Soaked Lightweight Aggregates as Additives for Internal Curing of High-Strength Concretes," *Cement, Concrete and Aggregates*, Vol. 26, No. 2, pp. 131–138.

Kranc, S. C., Sagues, A. A., and Presuel-Moreno, F. J., (2002). "Decreased Corrosion Initiation Time of Steel in Concrete Due to Reinforcing Bar Obstruction of Diffusional Flow," *ACI Materials Journal*, Vol. 99, No. 1, pp. 51–53.

Krauss, P. D., and Rogalla, E. A., (1996). "Transverse Cracking in Newly Constructed Bridge Decks," *NCHRP* 380, Transportation Research Board, Washington D.C., 126 pp.

Lam, H., and Hooton, R. D., (2005). "Effects of Internal Curing Methods on Restrained Shrinkage and Permeability," *Self-Desiccation and Its Importance in Concrete Technology*, B. Persson, D. Bentz, and L. O. Nilsson, eds., Lund Institute of Technology, Lund, Sweden, pp. 210–228.

Le, Q. T. C., French, C. E., and Hajjar, J., (1998). "Transverse Cracking in Bridge Decks: Parametric Study," *Final Report*, Minnesota Department of Transportation, St. Paul, Minnesota, 193 pp.

Lebet, J.-P., and Ducret, J.-M., (2000). "Early Concrete Cracking of Composite Bridges During Construction," American Society of Civil Engineers, Banff, Alta., Canada, pp. 13–24.

Lindquist, W. D., Darwin, D., and Browning, J., (2005). "Cracking and Chloride Contents in Reinforced Concrete Bridge Decks," *SM Report* No. 78, University of Kansas Center for Research, Inc., Lawrence, KS, 452 pp.

Lindquist, W. D., Darwin, D., and Browning, J., (2008). "Development and Construction of Low-Cracking High-Performance Concrete (LC-HPC) Bridge Decks: Free Shrinkage, Mixture Optimization, and Concrete Production," SM Report No. 92, University of Kansas Center for Research, Inc., Lawrence, KS, 504 pp.

Lindquist, W. D., Darwin, D., Browning, J., and Miller, G., (2006). "Effect of Cracking on Chloride Content in Concrete Bridge Decks," *ACI Materials Journal*, Vol. 103, No. 6, pp. 467–473.

Liu, Z., and Beaudoin, J. J., (2000). "The Permeability of Cement Systems to Chloride Ingress and Related Test Methods," *Cement, Concrete and Aggregates*, Vol. 22, No. 1, pp. 16–23.

Luping, T., and Nilsson, L.-O., (1992). "Rapid determination of the chloride diffusivity in concrete by applying an electrical field," *ACI Materials Journal*, Vol. 89, No. 1, pp. 40–53.

Lura, P., Bentz, D. P., Lange, D. A., Kovler, K., Bentur, A., and Van Breugel, K., (2006). "Measurement of Water Transport from Saturated Pumice Aggregates to Hardening Cement Paste," *Materials and Structures/Materiaux et Constructions*, Vol. 39, No. 293, pp. 861–868.

McGrath, P. F., and Hooton, R. D., (1999). "Re-evaluation of the AASHTO T259 90-Day Salt Ponding Test," *Cement and Concrete Research*, Vol. 29, No. 8, pp. 1239–1248.

McLeod, H. A. K., (2005). "Guide for Developing Optimized Concrete Mixtures," M.S. Thesis, University of Kansas, Lawrence, Kansas.

Miller, B. D., and Miltenberger, M. A., (2004). "Chloride Ingress into Concrete in Saturated and Cyclic Wetting and Drying Environments," *Eighth CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete*, SP-221, pp. 471–482.

Miller, G. G., and Darwin, D., (2000). "Performance and Constructability of Silica Fume Bridge Deck Overlays," *SM Report* No. 57, University of Kansas Center for Research, Inc., Lawrence, KS, 423 pp.

Mindess, S., Young, J. F., and Darwin, D., (2003). *Concrete*, 2nd ed., Pearson Education, Inc., Upper Saddle River, NJ, 644 pp.

Napier, C. S., and Maruri, R. F., (2003). "High Performance Concrete Survey Results," *High Performance Concrete Nationwide Survey (2003) Results*, Federal Highway Administration.

Neville, A. M., (1997). *Properties of Concrete*, 4th ed., John Wiley & Sons, Inc., New York.

Nokken, M., Boddy, A., Hooton, R. D., and Thomas, M. D. A., (2006). "Time Dependent Diffusion in Concrete - Three Laboratory Studies," *Cement and Concrete Research*, Vol. 36, No. 1, pp. 200–207.

NordTest NT Build 443, (1995). "Accelerated Chloride Penetrations," NordTest, Espoo, Finland, 5 pp.

NordTest NT Build 492, (1999). "Chloride Migration Coefficient from Non-Steady-State Migration Experiments," NordTest, Espoo, Finland, 8 pp.

Paulsson-Tralla, J., and Silfwerbrand, J., (2002). "Estimation of Chloride Ingress in Uncracked and Cracked Concrete Using Measured Surface Concentrations," *ACI Materials Journal*, Vol. 99, No. 1, pp. 27–36.

Perfetti, G. R., and Johnston, D. W., (1985). "Incidence Assessment of Transverse Cracking in Concrete Bridge Decks: Structural Considerations - Vol. 2," *Final Report*, Center for Transportation Engineering Studies, Department of Civil Engineering, North Carolina State University, Raleigh, North Carolina, 201 pp.

Pfeifer, D. W., McDonald, D. B., and Krauss, P. D., (1994). "The Rapid Chloride Permeability Test and its Correlation to the 90-Day Chloride Ponding Test," *PCI Journal*, Vol. 39, No. 1, pp. 38–47.

Phurkhao, P., and Kassir, M. K., (2005). "Note on Chloride-Induced Corrosion of Reinforced Concrete Bridge Decks," *Journal of Engineering Mechanics*, Vol. 131, No. 1, pp. 97–99.

Poppe, J. B., (1981). "Factors Affecting the Durability of Concrete Bridge Decks: Summary," *Final Report* FHWA/CA/SD-81/2, California Department of Transportation, Division of Transportation Facilities Design, Sacramento, California, 61 pp.

Portland Cement Association, (1970). "Durability of Concrete Bridge Decks - A Cooperative Study," *Final Report* EB067.01E, The state highway departments of California, Illinois, Kansas, Michigan, Minnesota, Missouri, New Jersey, Ohio, Texas, Virginia, U.S. Department of Transportation Bureau of Public Roads, and Portland Cement Association, 35 pp.

Portland Cement Association, (1996). "Portland Cement: Past and Present Characteristics," *Concrete Technology Today*, Vol. 17, No. 2, pp. 1–4.

Rogalla, E. A., Krauss, P. D., and McDonald, D. B., (1995). "Reducing Transverse Cracking in New Concrete Bridge Decks," *Concrete Construction*, Vol. 40, No. 9, pp. 735–738.

Russell, H., (2004). "Concrete Bridge Deck Performance - A Synthesis of Highway Practices," *NCHRP Synthesis* 333, Transportation Research Board, Washington, D.C., 101 pp.

Schmitt, T., and Darwin, D., (1995). "Cracking in Concrete Bridge Decks," *SM Report* No. 39, University of Kansas, Lawrence, KS, 151 pp.

Schmitt, T. R., and Darwin, D., (1999). "Effect of Material Properties on Cracking in Bridge Decks," *Journal of Bridge Engineering*, Vol. 4, No. 1, pp. 8–13.

Shi, C., Stegemann, J. A., and Caldwell, R. J., (1998). “Effect of Supplementary Cementing Materials on the Specific Conductivity of Pore Solution and its Implications on the Rapid Chloride Permeability Test (AASHTO T277 and ASTM C1202) Results,” *ACI Materials Journal*, Vol. 95, No. 4, pp. 389–394.

Shilstone, J. M., (1990). “Concrete Mixture Optimization,” *Concrete International*, Vol. 12, No. 6, pp. 33–39.

Smith, K. M., Schokker, A. J., and Tikalsky, P. J., (2004). “Performance of Supplementary Cementitious Materials in Concrete Resistivity and Corrosion Monitoring Evaluations,” *ACI Materials Journal*, Vol. 101, No. 5, pp. 385–390.

Sprinkel, M. M., and Ozyildirim, C., (1998). “Shrinkage of High-Performance Concrete Overlays on Route 60 in Virginia,” *Transportation Research Record*, No. 1610, pp. 15–19.

Suryavanshi, A. K., Swamy, R. N., and Cardew, G. E., (2002). “Estimation of Diffusion Coefficients for Chloride Ion Penetration into Structural Concrete,” *ACI Materials Journal*, Vol. 99, No. 5, pp. 441–449.

Thomas, M. D. A., (2006). “Chloride Diffusion in High-Performance Lightweight Aggregate Concrete,” *Seventh CANMET/ACI International Conference on Durability of Concrete*, SP-234, Montreal, Canada, pp. 799–812.

Thompson, N., Yunovich, M., and Dunmire, D. J., (2005). “Corrosion Costs and Maintenance Strategies - A Civil/Industrial and Government Partnership,” *Materials Performance*, Vol. 44, No. 9, pp. 16–20.

Tikalsky, P. J., Pustka, D., and Marek, P., (2005). “Statistical Variations in Chloride Diffusion in Concrete Bridges,” *ACI Structural Journal*, Vol. 102, No. 3, pp. 481–486.

Transportation Research Board, (2006). “Control of Cracking in Concrete: State of the Art,” *Report* E-C107, Transportation Research Board of the National Academies, Washington, D.C., 46 pp.

Virmani, Y. P., and Clemena, G. G., (1998). “Corrosion Protection - Concrete Bridges,” *Report* FHWA-RD-98-088, Federal Highway Administration, McLean, VA, McLean, VA, 80 pp.

Walther, R. A., and Chase, S. B., (2006). “Condition Assessment of Highway Structrures - Past, Present, and Future,” *Report* E-C104, Transportation Research Board, Washington, DC, 67–78 pp.

Webster, (1984). *Webster's Ninth New Collegiate Dictionary*, Merriam-Webster Inc., Springfield, MA.

Weyers, R. E., Fitch, M. G., Larsen, E. P., and Al-Qadi, I. L., (1994). “Concrete Bridge Protection and Rehabilitation: Chemical and Physical Techniques. Service Life Estimates,” *Report* SHRP-S-668, National Research Council, Washington D.C., 353 pp.

Whiting, D., and Detwiler, R., (1998). “Silica Fume Concrete for Bridge Decks,” *NCHRP Report* 410, Transportation Reserach Board, Washington D.C.

Whiting, D. A., Detwiler, R. J., and Lagergren, E. S., (2000). “Cracking Tendency and Drying Shrinkage of Silica Fume Concrete for Bridge Deck Applications,” *ACI Materials Journal*, Vol. 97, No. 1, pp. 71–77.

Whiting, D. A., and Mitchell, T., (1992). “History of the Rapid Chloride Permeability Test,” *Transportation Research Record*, Vol. 1335, No. 1, pp. 55–62.

Wojcik, G. S., Fitzjarrald, D. R., and Plawsky, J. L., (2003). “Modelling the Interaction Between the Atmosphere and Curing Concrete Bridge Decks with the SLABS Model,” *Meteorological Applications*, Vol. 10, No. 2, pp. 165–186.

Yazdani, N., Bergin, M., and Majtaba, H., (2000). “Effect of Pumping on Properties of Bridge Concrete,” *Journal of Materials in Civil Engineering*, Vol. 12, No. 3, pp. 212–219.

Yunovich, M., Thompson, N. G., and Virmani, Y. P., (2005). “Corrosion Protection System for Construction and Rehabilitation of Reinforced Concrete Bridges,” *International Journal of Materials and Product Technology*, Vol. 23, No. 3/4, pp. 269–285.

Zhutovsky, S., Kovler, K., and Bentur, A., (2002). “Efficiency of Lightweight Aggregates for Internal Curing of High Strength Concrete to Eliminate Autogenous Shrinkage,” *Materials and Structures/Materiaux et Constructions*, Vol. 35, No. 246, pp. 97–101.

APPENDIX A

CONCRETE MIXTURE PROPORTIONS AND PROPERTIES FOR PERMEABILITY TESTING

A.1 GENERAL

Appendix A contains the mix proportions and concrete properties for the seven permeability programs described in Chapter 2. The cementitious materials, aggreagates and chemical admixtures referenced in these tables are described in Chapter 2.

Table A.1 Program 1 mix proportions and concrete properties

Batch no.	**338**		**388**		**139**	
Batch designation	535 control 0.42		497 control 0.42		535 control 0.45	
w/cm	0.42		0.42		0.45	
Curing period, days	14		14		7	
Paste content, %	23.3		21.6		24.2	
Mix proportions kg/m^3 (lb/yd^3) and sample no.[i]						
Cementitious material						
Type I/II	318 (535)	4	295 (497)	5	318 (535)	1
Type II	-	-	-	-	-	-
Silica Fume	-	-	-	-	-	-
GGBFS Grade 100	-	-	-	-	-	-
Grade 120	-	-	-	-	-	-
Water	133 (223)		123 (207)		143 (241)	
Coarse aggregate						
Limestone	515 (867)	3(a)	558 (939)	5(a)	1008 (1695)	A
	312 (524)	3(a)	260 (438)	5(b)	-	-
Fine aggregate						
Kansas River sand	270 (454)	3	398 (669)	3	539 (906)	1
Pea gravel	692 (1164)	2	614 (1033)	5	219 (368)	A
Plasticizer, mL/m^3 (oz/yd^3)	1079 (27.9)[c]		1504 (38.9)[c]		523 (13.5)[a]	
AEA, mL/m^3 (oz/yd^3)	68 (1.8)[d]		85 (2.2)[d]		170 (4.4)[b]	
SRA, mL/m^3 (oz/yd^3)	-		-		-	
Batch properties						
Batch size, m^3 (yd^3)	0.050 (0.066)		0.041 (0.053)		0.050 (0.065)	
Slump, mm (in.)	50 (2)		95 (3.75)		31 (1.25)	
Design (measured) air content, %	8 (8.4)		8 (8.9)		8 (6.9)	
Temperature, °C (°F)	23 (73)		21 (70)		19 (66)	
Compressive strength, MPa (psi)						
7-day	28.8 (4170)		28.4 (4120)		-	
28-day	37.9 (5500)		28.5 (4130)		38.3 (5550)	

[i] – See Tables 2.1, 2.2, 2.3, 2.4, and 2.5 for gradations and chemical properties
[a] = Adva® 100 (Grace Construction Products)
[b] = Daravair® 1000 (Grace Construction Products)
[c] = Glenium® 3000 NS (BASF Construction Chemicals)
[d] = MicroAir® (BASF Construction Chemicals)
[e] = Tetraguard® AS20 (BASF Construction Chemicals)

Table A.1 (con't) Program 1 mix proportions and concrete properties

Batch no.	**148**		**347**		**351**	
Batch designation	497 control 0.45		535 – 60% G120		497 – 60% G120	
w/cm	0.45		0.42		0.42	
Curing period, days	7		14		14	
Paste content, %	22.5		23.2		21.6	
Mix proportions kg/m^3 (lb/yd^3) and sample no.[i]						
Cementitious material						
Type I/II	295 (497)	1	130 (219)	4	121 (204)	4
Type II	-	-	-	-	-	-
Silica Fume	-	-	-	-	-	-
GGBFS Grade 100	-	-	-	-	-	-
Grade 120	-	-	181 (305)	1	169 (284)	1
Water	133 (224)		130 (218)		121 (203)	
Coarse aggregate						
Limestone	1033 (1738)	A	515 (866)	3(a)	530 (891)	3(a)
	-	-	310 (522)	3(b)	322 (541)	3(b)
Fine aggregate						
Kansas River sand	552 (929)	1	266 (448)	3	284 (478)	3
Pea gravel	224 (377)	A	698 (1174)	2	696 (1171)	2
Plasticizer, mL/m^3 (oz/yd^3)	1341 (34.7)[a]		1050 (27.1)[c]		1031 (26.6)[c]	
AEA, mL/m^3 (oz/yd^3)	92 (2.4)[b]		128 (3.3)[d]		133 (3.4)[d]	
SRA, mL/m^3 (oz/yd^3)	-		-		-	
Batch properties						
Batch size, m^3 (yd^3)	0.046 (0.060)		0.050 (0.066)		0.050 (0.066)	
Slump, mm (in.)	100 (4)		95 (3.75)		55 (2.25)	
Design (measured) air content, %	8 (8.65)		8 (8.9)		8 (8.25)	
Temperature, °C (°F)	19 (66)		22 (72)		24 (75)	
Compressive strength, MPa (psi)						
7-day	-		29.2 (4230)		30.9 (4480)	
28-day	33.8 (4900)		32.9 (4770)		36.6 (5300)	

[i] – See Tables 2.1, 2.2, 2.3, 2.4, and 2.5 for gradations and chemical properties
[a] = Adva® 100 (Grace Construction Products)
[b] = Daravair® 1000 (Grace Construction Products)
[c] = Glenium® 3000 NS (BASF Construction Chemicals)
[d] = MicroAir® (BASF Construction Chemicals)
[e] = Tetraguard® AS20 (BASF Construction Chemicals)

Table A.1 (con't) Program 1 mix proportions and concrete properties

Batch no.	**354**		**355**	
Batch designation	497 – 60% G120 6% SF		460 – 60% G120 6% SF	
w/cm	0.42		0.42	
Curing period, days	14		14	
Paste content, %	21.6		20.5	
Mix proportions kg/m^3 (lb/yd^3) and sample no.[i]				
Cementitious material				
Type I/II	104 (175)	4	99 (166)	4
Type II	-	-	-	-
Silica Fume	12 (21)	1	12 (20)	1
GGBFS Grade 100	-	-	-	-
Grade 120	171 (287)	1	162 (272)	1
Water	120 (201)		112 (189)	
Coarse aggregate				
Limestone	529 (890)	3(a)	540 (908)	3(a)
	321 (540)	3(a)	329 (553)	3(b)
Fine aggregate				
Kansas River sand	282 (475)	3	295 (496)	3
Pea gravel	699 (1175)	2	697 (1173)	2
Plasticizer, mL/m^3 (oz/yd^3)	1507 (38.9)[c]		1962 (50.7)[c]	
AEA, mL/m^3 (oz/yd^3)	121 (3.1)[d]		131 (3.4)[d]	
SRA, mL/m^3 (oz/yd^3)	-		-	
Batch properties				
Batch size, m^3 (yd^3)	0.050 (0.066)		0.050 (0.066)	
Slump, mm (in.)	55 (2.25)		90 (3.5)	
Design (measured) air content, %	8 (8.9)		8 (8.9)	
Temperature, °C (°F)	22 (72)		24 (75)	
Compressive strength, MPa (psi)				
7-day	33.7 (4880)		31.8 (4610)	
28-day	39.8 (5770)		39.2 (5680)	

[i] – See Tables 2.1, 2.2, 2.3, 2.4, and 2.5 for gradations and chemical properties
[a] = Adva® 100 (Grace Construction Products)
[b] = Daravair® 1000 (Grace Construction Products)
[c] = Glenium® 3000 NS (BASF Construction Chemicals)
[d] = MicroAir® (BASF Construction Chemicals)
[e] = Tetraguard® AS20 (BASF Construction Chemicals)

Table A.2 Program 2[†] mix proportions and concrete properties

Batch no.	**141**		**161**	
Batch designation	7-day cure 0.45		14-day cure 0.45	
w/cm	0.45		0.45	
Curing period, days	7		14	
Paste content, %	24.2		24.2	
Mix proportions kg/m^3 (lb/yd^3) and sample no.[i]				
Cementitious material				
Type I/II	318 (535)	1	318 (535)	1
Type II	-	-	-	-
Silica Fume	-	-	-	-
GGBFS Grade 100	-	-	-	-
Grade 120	-	-	-	-
Water	143 (241)		143 (241)	
Coarse aggregate				
Limestone	1008 (1695)	B	1008 (1695)	B
	-	-	-	-
Fine aggregate				
Kansas River sand	539 (906)	1	539 (906)	1
Pea gravel	219 (368)	A	219 (368)	A
Plasticizer, mL/m^3 (oz/yd^3)	523 (13.5)[a]		891 (23.0)[a]	
AEA, mL/m^3 (oz/yd^3)	170 (4.4)[b]		222 (5.7)[b]	
SRA, mL/m^3 (oz/yd^3)	-		-	
Batch properties				
Batch size, m^3 (yd^3)	0.050 (0.065)		0.050 (0.065)	
Slump, mm (in.)	75 (3)		63 (2.5)	
Design (measured) air content, %	8 (7.65)		8 (7.4)	
Temperature, °C (°F)	19 (67)		24 (76)	
Compressive strength, MPa (psi)				
7-day	-		-	
28-day	37.0 (5360)		37.3 (5410)	

[†] Program 2 also includes Batch 139 (shown in Table A.1).
[i] See Tables 2.1, 2.2, 2.3, 2.4, and 2.5 for gradations and chemical properties
[a] = Adva® 100 (Grace Construction Products)
[b] = Daravair® 1000 (Grace Construction Products)
[c] = Glenium® 3000 NS (BASF Construction Chemicals)
[d] = MicroAir® (BASF Construction Chemicals)
[e] = Tetraguard® AS20 (BASF Construction Chemicals)

Table A.2 (con't) Program 2† mix proportions and concrete properties

Batch no.	**144**		**164**	
Batch designation	CG II		CG II	
w/cm	0.45		0.45	
Curing period, days	7		7, 14, 28	
Paste content, %	24.2		24.2	
Mix proportions kg/m^3 (lb/yd^3) and sample no.[i]				
Cementitious material				
Type I/II	-	-	-	-
Type II	318 (535)	1	318 (535)	1
Silica Fume	-	-	-	-
GGBFS Grade 100	-	-	-	-
Grade 120	-	-	-	-
Water	143 (241)		143 (241)	
Coarse aggregate				
Limestone	1009 (1697)	A	1009 (1697)	B
	-	-	-	-
Fine aggregate				
Kansas River sand	539 (906)	1	539 (906)	1
Pea gravel	219 (368)	A	219 (368)	A
Plasticizer, mL/m^3 (oz/yd^3)	360 (9.3)[c]		392 (10.1)[c]	
AEA, mL/m^3 (oz/yd^3)	213 (5.5)[d]		118 (3.0)[d]	
SRA, mL/m^3 (oz/yd^3)			-	
Batch properties				
Batch size, m^3 (yd^3)	0.050 (0.065)		0.153 (0.200)	
Slump, mm (in.)	75 (3)		56 (2.25)	
Design (measured) air content, %	8 (8.65)		8 (8.4)	
Temperature, °C (°F)	20 (68)		22 (72)	
Compressive strength, MPa (psi)				
7-day	28.8 (4170)		21.0 (3050)	
28-day	37.9 (5500)		24.1 (3500)	

† Program 2 also includes Batch 139 (shown in Table A.1).
[i] See Tables 2.1, 2.2, 2.3, 2.4, and 2.5 for gradations and chemical properties
[a] = Adva® 100 (Grace Construction Products)
[b] = Daravair® 1000 (Grace Construction Products)
[c] = Glenium® 3000 NS (BASF Construction Chemicals)
[d] = MicroAir® (BASF Construction Chemicals)
[e] = Tetraguard® AS20 (BASF Construction Chemicals)

Table A.2 (con't) Program 2† mix proportions and concrete properties

Batch no.	234		235		239	
Batch designation	I/II 0.41		I/II 0.43		I/II 0.45	
w/cm	0.41		0.43		0.45	
Curing period, days	7, 14		7, 14		7, 14	
Paste content, %	23.1		23.7		24.4	
Mix proportions kg/m^3 (lb/yd^3) and sample no.[i]						
Cementitious material						
Type I/II	317 (535)	2	317 (535)	2	318 (535)	3
Type II	-	-	-	-	-	-
Silica Fume	-	-	-	-	-	-
GGBFS Grade 100	-	-	-	-	-	-
Grade 120	-	-	-	-	-	-
Water	130 (219)		136 (230)		143 (241)	
Coarse aggregate						
Limestone	882 (1486)	C	873 (1472)	C	865 (1458)	C
	-	-	-	-	-	-
Fine aggregate						
Kansas River sand	557 (938)	2	558 (941)	2	546 (921)	2
Pea gravel	355 (598)	B	352 (593)	B	348 (587)	B
Plasticizer, mL/m^3 (oz/yd^3)	994 (25.7)[c]		860 (22.2)[c]		327 (8.5)[c]	
AEA, mL/m^3 (oz/yd^3)	77 (2.0)[d]		55 (1.4)[d]		92 (2.4)[d]	
SRA, mL/m^3 (oz/yd^3)	-		-		-	
Batch properties						
Batch size, m^3 (yd^3)	0.131 (0.171)		0.131 (0.171)		0.131 (0.171)	
Slump, mm (in.)	70 (2.75)		90 (3.5)		80 (3.25)	
Design (measured) air content, %	8 (8.65)		8 (8.15)		8 (8.15)	
Temperature, °C (°F)	21 (69)		22 (72)		24 (75)	
Compressive strength, MPa (psi)						
7-day strength	-		-		-	
28-day strength††						
3-day wet cure	31.4 (4550)		31.6 (4580)		26.0 (3770)	
7-day wet cure	29.6 (4300)		31.4 (4560)		28.4 (4120)	
14-day wet cure	33.6 (4880)		32.1 (4660)		28.3 (4110)	
28-day wet cure	31.0 (4500)		31.7 (4600)		28.1 (4080)	

† Program 2 also includes Batch 139 (shown in Table A.1).
†† Cylinders were cured for 3, 7, 14, or 28 days in lime-saturated water and then transferred to a drying tent [22°C (73°F) and 50% RH] for the balance of 28 days.
[i] See Tables 2.1, 2.2, 2.3, 2.4, and 2.5 for gradations and chemical properties
[c] = Glenium® 3000 NS (BASF Construction Chemicals)
[d] = MicroAir® (BASF Construction Chemicals)

Table A.2 (con't) Program 2† mix proportions and concrete properties

Batch no.	240		244		246	
Batch designation	MG II 0.41		MG II 0.43		MG II 0.45	
w/cm	0.41		0.43		0.45	
Curing period, days	7, 14		7, 14		7, 14	
Paste content, %	23.1		23.7		24.4	
Mix proportions kg/m³ (lb/yd³) and sample no.[i]						
Cementitious material						
Type I/II	-	-	-	-	-	-
Type II	317 (535)	2	317 (535)	2	317 (535)	2
Silica Fume	-	-	-	-	-	-
GGBFS Grade 100	-	-	-	-	-	-
Grade 120	-	-	-	-	-	-
Water	130 (219)		136 (230)		143 (241)	
Coarse aggregate						
Limestone	882 (1486)	C	516 (869)	D(a)	510 (860)	D(a)
	-	-	322 (542)	D(b)	318 (536)	D(b)
Fine aggregate						
Kansas River sand	557 (938)	2	422 (712)	2	418 (704)	2
Pea gravel	355 (598)	B	520 (876)	C	514 (866)	C
Plasticizer, mL/m³ (oz/yd³)	994 (25.7)[c]		360 (9.3)[c]		117 (3.0)[c]	
AEA, mL/m³ (oz/yd³)	72 (1.9)[d]		120 (3.1)[d]		172 (4.4)[d]	
SRA, mL/m³ (oz/yd³)	-		-		-	
Batch properties						
Batch size, m³ (yd³)	0.131 (0.171)		0.131 (0.171)		0.131 (0.171)	
Slump, mm (in.)	75 (3)		80 (3.25)		70 (2.75)	
Design (measured) air content, %	8 (8.65)		8 (8.15)		8 (7.9)	
Temperature, °C (°F)	23 (74)		23 (74)		21 (70)	
Compressive strength, MPa (psi)						
7-day strength	-		-		-	
28-day strength††						
3-day wet cure	27.9 (4050)		23.4 (3400)		22.3 (3230)	
7-day wet cure	28.0 (4060)		25.1 (3640)		24.6 (3570)	
14-day wet cure	28.5 (4140)		26.4 (3830)		26.3 (3810)	
28-day wet cure	28.6 (4150)		26.5 (3840)		26.0 (3770)	

† Program 2 also includes Batch 139 (shown in Table A.1).
†† Cylinders were cured for 3, 7, 14, or 28 days in lime-saturated water and then transferred to a drying tent [22°C (73°F) and 50% RH] for the balance of 28 days.
[i] See Tables 2.1, 2.2, 2.3, 2.4, and 2.5 for gradations and chemical properties
[c] = Glenium® 3000 NS (BASF Construction Chemicals)
[d] = MicroAir® (BASF Construction Chemicals)

Table A.3 Program 3[†] mix proportions and concrete properties

Batch no.	**330**		**334**		**335**	
Batch designation	0.36 *w/cm*		0.38 *w/cm*		0.40 *w/cm*	
w/cm	0.36		0.38		0.40	
Curing period, days	14		14		14	
Paste content, %	23.3		23.3		23.2	
Mix proportions kg/m^3 (lb/yd^3) and sample no.[i]						
Cementitious material						
Type I/II	347 (583)	4	337 (566)	4	327 (550)	4
Type II	-	-	-	-	-	-
Silica Fume	-	-	-	-	-	-
GGBFS Grade 100	-	-	-	-	-	-
Grade 120	-	-	-	-	-	-
Water	123 (207)		127 (213)		130 (218)	
Coarse aggregate						
Limestone	511 (860)	3(a)	512 (862)	3(a)	514 (865)	3(a)
	306 (515)	3(b)	308 (518)	3(b)	310 (521)	3(b)
Fine aggregate						
Kansas River sand	256 (430)	3	260 (438)	3	266 (447)	3
Pea gravel	715 (1203)	2	707 (1189)	2	699 (1176)	2
Plasticizer, mL/m^3 (oz/yd^3)	2128 (55.0)[c]		1635 (42.3)[c]		1308 (33.8)[c]	
AEA, mL/m^3 (oz/yd^3)	64 (1.7)[d]		70 (1.8)[d]		73 (1.9)[d]	
SRA, mL/m^3 (oz/yd^3)	-		-		-	
Batch properties						
Batch size, m^3 (yd^3)	0.050 (0.066)		0.050 (0.066)		0.050 (0.066)	
Slump, mm (in.)	95 (3.75)		75 (3)		50 (2)	
Design (measured) air content, %	8 (8.15)		8 (8.4)		8 (8.65)	
Temperature, °C (°F)	23 (73)		22 (72)		22 (72)	
Compressive strength, MPa (psi)						
7-day	45.9 (6660)		39.0 (5650)		30.8 (4460)	
28-day	50.7 (7350)		43.0 (6230)		38.8 (5630)	

[†] Program 3 also includes Batches 139, and 338 (shown in Table A.1), and Batches 234, 235, 239, 141, 161, 240, 244, 246, 164, and 144 (shown in Table A.2).
[i] See Tables 2.1, 2.2, 2.3, 2.4, and 2.5 for gradations and chemical properties
[a] = Adva® 100 (Grace Construction Products)
[b] = Daravair® 1000 (Grace Construction Products)
[c] = Glenium® 3000 NS (BASF Construction Chemicals)
[d] = MicroAir® (BASF Construction Chemicals)
[e] = Tetraguard® AS20 (BASF Construction Chemicals)

Table A.4 Program 4[†] mix proportions and concrete properties

Batch no. [†]	[†]
Batch designation *w/cm* Curing period, days Paste content, %	
Mix proportions kg/m^3 (lb/yd^3) and sample no.[i]	
Cementitious material Type I/II Type II Silica Fume GGBFS Grade 100 Grade 120	
Water	
Coarse aggregate Limestone	
Fine aggregate Kansas River sand Pea gravel	
Plasticizer, mL/m^3 (oz/yd^3)	
AEA, mL/m^3 (oz/yd^3)	
SRA, mL/m^3 (oz/yd^3)	
Batch properties	
Batch size, m^3 (yd^3)	
Slump, mm (in.)	
Design (measured) air content, %	
Temperature, °C (°F)	
Compressive strength, MPa (psi) 7-day 28-day	

[†] Program 4 includes Batches 139 (shown in Table A.1), and Batches 141, 144, 161, 164, 234, 235, 239, 240, 244, and 246 (shown in Table A.2).
[i] See Tables 2.1, 2.2, 2.3, 2.4, and 2.5 for gradations and chemical properties
[a] = Adva® 100 (Grace Construction Products)
[b] = Daravair® 1000 (Grace Construction Products)
[c] = Glenium® 3000 NS (BASF Construction Chemicals)
[d] = MicroAir® (BASF Construction Chemicals)
[e] = Tetraguard® AS20 (BASF Construction Chemicals)

Table A.5 Program 5† mix proportions and concrete properties

Batch no.	**328**		**358**		**378**	
Batch designation	535 – 60% G100		460 – 80% G120 6% SF		535 – 60% G100 6% SF	
w/cm	0.42		0.42		0.42	
Curing period, days	14		14		14	
Paste content, %	23.3		20.5		23.3	
Mix proportions kg/m^3 (lb/yd^3) and sample no.[i]						
Cementitious material						
Type I/II	132 (222)	4	41 (69)	4	114 (191)	5
Type II	-	-	-	-	-	-
Silica Fume	-	-	12 (20)	1	14 (23)	1
GGBFS Grade 100	177 (298)	1	-	-	180 (302)	2
Grade 120	-	-	218 (366)	1	-	-
Water	129 (217)		112 (188)		129 (217)	
Coarse aggregate						
Limestone	514 (864)	3(a)	540 (908)	3(a)	518 (871)	4(a)
	309 (520)	3(b)	328 (552)	3(b)	306 (515)	3(b)
Fine aggregate						
Kansas River sand	264 (444)	3	294 (494)	3	264 (444)	3
Pea gravel	702 (1180)	2	699 (1176)	2	699 (1175)	2
Plasticizer, mL/m^3 (oz/yd^3)	1150 (29.7)[c]		1834 (47.4)[c]		1328 (34.3)[c]	
AEA, mL/m^3 (oz/yd^3)	144 (3.7)[d]		167 (4.3)[d]		99 (2.6)[d]	
SRA, mL/m^3 (oz/yd^3)	-		-		-	
Batch properties						
Batch size, m^3 (yd^3)	0.050 (0.066)		0.050 (0.066)		0.050 (0.066)	
Slump, mm (in.)	80 (3.25)		75 (3)		70 (2.75)	
Design (measured) air content, %	8 (8.9)		8 (8.4)		8 (8.9)	
Temperature, °C (°F)	20 (68)		22 (72)		22 (71)	
Compressive strength, MPa (psi)						
7-day	26.4 (3830)		26.9 (3900)		28.2 (4090)	
28-day	35.2 (5110)		32.5 (4710)		37.2 (5390)	

† Program 5 also includes Batches 338, 347, 351, 354, 355, and 388 (shown in Table A.1).
[i] See Tables 2.1, 2.2, 2.3, 2.4, and 2.5 for gradations and chemical properties
[a] = Adva® 100 (Grace Construction Products)
[b] = Daravair® 1000 (Grace Construction Products)
[c] = Glenium® 3000 NS (BASF Construction Chemicals)
[d] = MicroAir® (BASF Construction Chemicals)
[e] = Tetraguard® AS20 (BASF Construction Chemicals)

Table A.5 (con't) Program 5† mix proportions and concrete properties

Batch no.	**381**		**380**		**424**	
Batch designation	3% SF		6% SF		535 – 30% G120	
w/cm	0.42		0.42		0.42	
Curing period, days	14		14		14	
Paste content, %	23.3		23.2		23.3	
Mix proportions kg/m^3 (lb/yd^3) and sample no.[i]						
Cementitious material						
Type I/II	310 (522)	5	302 (508)	5	227 (381)	5
Type II	-	-	-	-	-	-
Silica Fume	7 (11)	1	13 (22)	1	-	-
GGBFS Grade 100	-	-	-	-	-	-
Grade 120	-	-	-	-	88 (148)	1
Water	132 (222)		131 (221)		131 (221)	
Coarse aggregate						
Limestone	519 (873)	4(a)	519 (873)	4(a)	538 (905)	5(a)
	309 (520)	3(b)	309 (520)	3(b)	286 (481)	5(b)
Fine aggregate						
Kansas River sand	271 (456)	3	271 (455)	3	378 (636)	4
Pea gravel	688 (1158)	2	690 (1160)	2	586 (985)	6
Plasticizer, mL/m^3 (oz/yd^3)	1237 (32.0)[c]		1237 (32.0)[c]		1050 (27.1)[c]	
AEA, mL/m^3 (oz/yd^3)	54 (1.4)[d]		63 (1.6)[d]		99 (2.6)[d]	
SRA, mL/m^3 (oz/yd^3)	-		-		-	
Batch properties						
Batch size, m^3 (yd^3)	0.041 (0.053)		0.041 (0.053)		0.050 (0.066)	
Slump, mm (in.)	57 (2.25)		50 (2)		50 (2)	
Design (measured) air content, %	8 (7.9)		8 (8.65)		8 (8.9)	
Temperature, °C (°F)	22 (72)		22 (71)		22 (72)	
Compressive strength, MPa (psi)						
7-day	29.1 (4220)		31.7 (4600)		30.9 (4480)	
28-day	41.2 (5980)		39.4 (5710)		41.1 (5960)	

† Program 5 also includes Batches 338, 347, 351, 354, 355, and 388 (shown in Table A.1).
[i] See Tables 2.1, 2.2, 2.3, 2.4, and 2.5 for gradations and chemical properties
[a] = Adva® 100 (Grace Construction Products)
[b] = Daravair® 1000 (Grace Construction Products)
[c] = Glenium® 3000 NS (BASF Construction Chemicals)
[d] = MicroAir® (BASF Construction Chemicals)
[e] = Tetraguard® AS20 (BASF Construction Chemicals)

Table A.6 Program 6[†] mix proportions and concrete properties

Batch no.	146		385	
Batch designation	2% SRA 0.45		1% SRA 0.42	
w/cm	0.45		0.42	
Curing period, days	7		14	
Paste content, %	24.2		23.3	
Mix proportions kg/m^3 (lb/yd^3) and sample no.[i]				
Cementitious material				
Type I/II	318 (535)	1	318 (535)	5
Type II	-	-	-	-
Silica Fume	-	-	-	-
GGBFS Grade 100	-	-	-	-
Grade 120	-	-	-	-
Water	137 (230)		129 (217)	
Coarse aggregate				
Limestone	1008 (1695)	A	537 (904)	5(a)
	-	-	288 (485)	4(b)
Fine aggregate				
Kansas River sand	539 (906)	1	262 (441)	3
Pea gravel	219 (368)	A	700 (1177)	2
Plasticizer, mL/m^3 (oz/yd^3)	491 (12.7)[c]		1275 (33.0)[c]	
AEA, mL/m^3 (oz/yd^3)	1046 (27.0)[d]		154 (4.0)[d]	
SRA, mL/m^3 (oz/yd^3)	6413 (165.8)[e]		3176 (82.1)[e]	
Batch properties				
Batch size, m^3 (yd^3)	0.050 (0.065)		0.041 (0.053)	
Slump, mm (in.)	25 (1)		76 (3)	
Design (measured) air content, %	8 (9.15)		8 (8.65)	
Temperature, °C (°F)	21 (69)		22 (71)	
Compressive strength, MPa (psi)				
7-day	-		37.0 (5360)	
28-day	32.1 (4650)		44.7 (6480)	

[†] Program 6 also includes Batches 139 and 338 (shown in Table A.1).
[i] See Tables 2.1, 2.2, 2.3, 2.4, and 2.5 for gradations and chemical properties
[a] = Adva® 100 (Grace Construction Products)
[b] = Daravair® 1000 (Grace Construction Products)
[c] = Glenium® 3000 NS (BASF Construction Chemicals)
[d] = MicroAir® (BASF Construction Chemicals)
[e] = Tetraguard® AS20 (BASF Construction Chemicals)

Table A.7 Program 7[†] mix proportions and concrete properties

Batch no.	**131**		**133**		**387**	
Batch designation	KDOT		MoDOT		KDOT	
w/cm	0.44		0.37		0.44	
Curing period, days	7		7		14	
Paste content, %	26.9		29.6		26.9	
Mix proportions kg/m^3 (lb/yd^3) and sample no.[i]						
Cementitious material						
Type I/II	358 (602)	1	433 (729)	1	358 (602)	5
Type II	-	-	-	-	-	-
Silica Fume	-	-	-	-	-	-
GGBFS Grade 100	-	-	-	-	-	-
Grade 120	-	-	-	-	-	-
Water	158 (265)		161 (271)		157 (264)	
Coarse aggregate						
Limestone	876 (1474)	A	1061 (1785)	A	866 (1456)	5
	-	-	-	-	-	-
Fine aggregate						
Kansas River sand	873 (1469)	1	641 (1078)	1	866 (1456)	3
Pea gravel	-	-	-	-	-	-
Plasticizer, mL/m^3 (oz/yd^3)	327 (8.5)[a]		379 (9.8)[a]		916 (23.7)[c]	
AEA, mL/m^3 (oz/yd^3)	157 (4.1)[b]		412 (10.7)[b]		27 (0.7)[d]	
SRA, mL/m^3 (oz/yd^3)	-		-		-	
Batch properties						
Batch size, m^3 (yd^3)	0.046 (0.060)		0.050 (0.065)		0.050 (0.066)	
Slump, mm (in.)	144 (5.75)		25 (1)		171 (6.75)	
Design (measured) air content, %	6 (8.9)		5 (5.4)		6.5 (5.9)	
Temperature, °C (°F)	21 (70)		19 (67)		22 (71)	
Compressive strength, MPa (psi)						
7-day	-		-		33.4 (4850)	
28-day	34.2 (4960)		No Results		40.4 (5860)	

[†] Program 7 also includes Batches 139 and 338 (shown in Table A.1).
[i] See Tables 2.1, 2.2, 2.3, 2.4, and 2.5 for gradations and chemical properties
[a] = Adva® 100 (Grace Construction Products)
[b] = Daravair® 1000 (Grace Construction Products)
[c] = Glenium® 3000 NS (BASF Construction Chemicals)
[d] = MicroAir® (BASF Construction Chemicals)
[e] = Tetraguard® AS20 (BASF Construction Chemicals)

APPENDIX B

CHLORIDE TESTING DATA

B.1 GENERAL

Appendix B contains the raw data on chloride concentration raw data and the chloride profiles for individual specimens for the permeability testing described in Chapters 2 and 3. The raw data is given in Table B.1. The three specimen indicators, A, B, and C, correspond to the three specimens from the same concrete batch for each permeability test. Some tests of samples for chloride concentration have been repeated as noted. Chloride profiles are shown in Figs. (B.1) through (B.41). The data points omitted from the analysis are noted in Table B.1 and in the figures.

The drying time between deponding and lathe sampling for each of the batches is provided in Table B.2.

Table B.1 Chloride concentration raw data

Batch number:	131		
Casting date:	6/21/2004		
Description:	26.9%-602-100% I/II-0.44-KDOT		
Average Sample Depth (mm)	Chloride Concentration [Cl-] (lb/yd^3)		
Specimen	A	B	C
2	8.26	8.70	8.70
6	6.56	6.43	6.74
11.5	4.22	4.35	4.54
18	1.76	1.70	2.08
22.5	0.88	0.82	0.95
Program and Set Numbers (Program-Set)			7-1

Batch number:	133		
Casting date:	6/22/2004		
Description:	29.6%-729-100% I/II-0.37-MoDOT modified		
Average Sample Depth (mm)	Chloride Concentration [Cl-] (lb/yd^3)		
Specimen	A	B	C
2	8.76	9.40	8.88
6	6.52	6.61	6.33
11.5	3.64	3.99	3.96
18	1.15	1.21	1.21
22.5	0.77	0.64	0.72
Program and Set Numbers (Program-Set)			7-1

Batch number:	**139**					
Casting date:	6/24/2004					
Description:	24.2%-535-100% I/II-0.45					
Average Sample Depth (mm)	**Chloride Concentration [Cl-] (lb/yd^3)**					
Specimen	**A**	**B**	**C**			
2	7.81	8.43	8.12			
6	5.58	5.89	6.07			
11.5	3.59	4.21	3.66			
18	1.12	1.49	1.43			
22.5	0.76	1.38	0.76			
Program and Set Numbers (Program-Set)			1-2	2-1	4-1	6-1
			7-1			

Batch number:	**141**					
Casting date:	6/25/2004					
Description:	24.2%-535-100% I/II-0.45					
Average Sample Depth (mm)	**Chloride Concentration [Cl-] (lb/yd^3)**					
Specimen	**A**	**B**	**C**	**B-Repeat 1**	**B-Repeat 2**	**B-Repeat 3**
2	8.36	8.36	8.36	8.18	-	-
6	5.51	5.58	6.26	5.64	-	-
11.5	3.78	3.41	3.97	3.53	-	-
18	1.98	1.61	1.73	1.24	-	-
22.5	0.99	0.64	0.95	0.45	0.43	0.58
Program and Set Numbers (Program-Set)			2-1	4-1		

Batch number:	144		
Casting date:	6/26/2004		
Description:	24.2%-535-100% CG II-0.45		
Average Sample Depth (mm)	Chloride Concentration [Cl-] (lb/yd^3)		
Specimen	A	B	C
2	6.69	6.63	8.55
4	5.27	-	-
6	5.51	5.58	6.57
11.5	3.78	3.97	4.40
18	2.17	2.35	2.29
22.5	1.30	1.43	1.61
Program and Set Numbers (Program-Set)		2-2	4-1

Batch number:	146		
Casting date:	6/28/2004		
Description:	24.2%-535-100% I/II-0.45-2% SRA		
Average Sample Depth (mm)	Chloride Concentration [Cl-] (lb/yd^3)		
Specimen	A	B	C
2	8.80	9.17	7.87
6	5.61	6.07	5.70
11.5	3.47	3.84	3.28
18	1.32	1.63	1.63
22.5	0.89	0.70	0.95
Program and Set Numbers (Program-Set)		6-1	

Batch number:	148				
Casting date:	6/29/2004				
Description:	22.5%-497-100% I/II-0.45				
Average Sample Depth (mm)	**Chloride Concentration [Cl-] (lb/yd^3)**				
Specimen	**A**	**B**	**C**		
2	7.10	7.29	8.53		
6	5.92	5.86	6.04		
11.5	3.55	3.86	3.36		
18	1.78	1.81	2.37		
22.5	0.95	0.95	0.50		
Program and Set Numbers (Program-Set)			1-2		

Batch number:	161				
Casting date:	7/14/2004				
Description:	24.2%-535-100% I/II-0.45				
Average Sample Depth (mm)					
Specimen	**A**	**B**	**C**	**B-Repeat 1**	**B-Repeat 2**
2	7.13	7.44	7.13	6.63†	NA††
6	5.95	6.63	6.13	6.10†	7.75†
11.5	3.28	5.14	3.72	4.52†	4.83†
18	1.01	1.50	1.30	2.66†	3.28†
22.5	0.51	0.20	0.82	2.11†	2.04†
Program and Set Numbers (Program-Set)			2-1	4-2	

† Removed from analysis

†† Not available

Batch number:	164-7			
Casting date:	7/21/2004			
Description:	24.2%-535-100% CG II-0.45			
Average Sample Depth (mm)	Chloride Concentration [Cl-] (lb/yd^3)			
Specimen	A	B	C	A-Repeat 1
2	5.58†	8.00	7.19	NA††
4	-	-	-	5.64†
6	3.66†	6.20	6.26	3.63†
11.5	3.10†	3.53	4.03	2.85†
18	2.29†	2.36	2.36	-
22.5	1.30†	1.49	1.55	-
Program and Set Numbers (Program-Set)			2-2	4-1

Batch number:	164-14			
Casting date:	7/21/2004			
Description:	24.2%-535-100% CG II-0.45			
Average Sample Depth (mm)	Chloride Concentration [Cl-] (lb/yd^3)			
Specimen	A	B	C	B-Repeat 1
2	7.87	7.56	7.44	-
6	5.21	6.32	5.64	-
11.5	3.41	3.35	3.78	-
18	1.92	2.54	1.98	2.15
22.5	0.89	2.36†	0.89	1.49
Program and Set Numbers (Program-Set)			2-2	4-2

Batch number:	164-28		
Casting date:	7/21/2004		
Description:	24.2%-535-100% CG II-0.45		
Average Sample Depth (mm)	Chloride Concentration [Cl-] (lb/yd^3)		
Specimen	A	B	C
2	6.82	7.01	7.75
6	4.90	4.96	5.58
11.5	3.41	3.29	3.47
18	1.55	1.67	1.80
22.5	0.89	0.70	0.95
Program and Set Numbers (Program-Set)			2-2

Batch number:	234-7			
Casting date:	6/27/2005			
Description:	23.1%-535-100% I/II-0.41			
Average Sample Depth (mm)	Chloride Concentration [Cl-] (lb/yd^3)			
Specimen	A	B	C	
2	9.25	10.50	10.81	
6	6.87	7.56	7.25	
11.5	3.81	4.69	4.40	
18	1.25	1.81	1.19	
22.5	0.62	0.56	0.56	
Program and Set Numbers (Program-Set)		2-3	3-1	4-7

Batch number:	234-14				
Casting date:	6/27/2005				
Description:	23.1%-535-100% I/II-0.41				
Average Sample Depth (mm)	Chloride Concentration [Cl-] (lb/yd^3)				
Specimen	D	E	F	A-Repeat 1	
2	10.75	10.31	10.06		
6	7.62	5.93	7.18		
11.5	3.87	2.94	3.94		
18	1.06	0.81	1.56	1.06	
22.5	0.37	0.37	0.81	0.69	
Program and Set Numbers (Program-Set)			2-3	3-2	4-8

Batch number:	**235-7**			
Casting date:	6/30/2005			
Description:	23.1%-535-100% I/II-0.41			
Average Sample Depth (mm)	**Chloride Concentration [Cl-] (lb/yd^3)**			
Specimen	**A**	**B**	**C**	**A-Repeat 1**
2	9.83	9.14	8.83	-
4	-	-	-	10.08
6	8.58	6.10	5.54	-
11.5	6.53	3.48	2.99	6.03
18	3.89	1.09	0.75	3.61
22.5	1.68	0.59	0.31	2.30
Program and Set Numbers (Program-Set)		2-5	3-1	4-5

Batch number:	**235-14**			
Casting date:	6/30/2005			
Description:	23.1%-535-100% I/II-0.41			
Average Sample Depth (mm)	**Chloride Concentration [Cl-] (lb/yd^3)**			
Specimen	**D**	**E**	**F**	
2	9.95	10.02	10.82	
6	7.43	6.03	6.84	
11.5	3.59	3.30	3.39	
18	0.75	0.68	0.93	
22.5	0.31	0.25	0.40	
Program and Set Numbers (Program-Set)		2-5	3-2	4-6

Batch number:	239-7				
Casting date:	7/8/2005				
Description:	24.4%-535-100% I/II-0.45				
Average Sample Depth (mm)	Chloride Concentration [Cl-] (lb/yd^3)				
Specimen	A	B	C		
2	9.91	10.96	11.64		
6	6.50	6.44	6.69		
11.5	4.71	3.84	4.40		
18	1.67	1.05	1.73		
22.5	0.56	0.34	0.68		
Program and Set Numbers (Program-Set)			2-7	3-1	4-3

Batch number:	239-14				
Casting date:	7/8/2005				
Description:	24.4%-535-100% I/II-0.45				
Average Sample Depth (mm)	Chloride Concentration [Cl-] (lb/yd^3)				
Specimen	D	E	F		
2	10.71	9.91	11.27		
6	6.87	5.70	6.25		
11.5	4.40	2.79	4.12		
18	1.18	0.62	0.99		
22.5	0.37	0.28	0.48		
Program and Set Numbers (Program-Set)			2-7	3-2	4-4

Batch number:	240-7					
Casting date:	7/13/2005					
Description:	23.1%-535-100% MG II-0.41					
Average Sample Depth (mm)	Chloride Concentration [Cl-] (lb/yd^3)					
Specimen	A	B	C			
2	9.43	8.68	8.25			
6	6.87	7.06	5.81			
11.5	4.06	4.81	2.37			
18	1.75	2.81	0.81			
22.5	0.40	1.69	0.31			
Program and Set Numbers (Program-Set)			2-4	3-3	4-7	

Batch number:	240-14					
Casting date:	7/14/2005					
Description:	23.1%-535-100% MG II-0.41					
Average Sample Depth (mm)	Chloride Concentration [Cl-] (lb/yd^3)					
Specimen	D	E	F	D-Repeat 1		
2	3.50	9.50	8.56	4.31		
6	3.56	5.81	4.12	3.12		
11.5	2.00	3.62	3.00	2.56		
18	0.56	1.25	1.03	0.84		
22.5	0.25	0.62	0.44	0.41		
Program and Set Numbers (Program-Set)			2-4	3-4	4-8	

Batch number:	244-7				
Casting date:	7/20/2005				
Description:	23.7%-535-100% MG II-0.43				
Average Sample Depth (mm)	Chloride Concentration [Cl-] (lb/yd^3)				
Specimen	A	B	C	C-Repeat 1	
2	8.03	8.97	8.84	-	
6	5.42	6.23	6.60	-	
11.5	3.71	3.61	4.23	-	
18	1.37	1.49	1.62	-	
22.5	0.78	0.62	1.43	0.75	
Program and Set Numbers (Program-Set)			2-6	3-3	4-5

Batch number:	244-14				
Casting date:	7/20/2005				
Description:	23.7%-535-100% MG II-0.43				
Average Sample Depth (mm)	Chloride Concentration [Cl-] (lb/yd^3)				
Specimen	D	E	F	D-Repeat 1	E-Repeat 1
2	8.44	9.71	8.47	-	-
6	6.07	6.51	6.48	-	-
11.5	3.99	4.30	4.36	-	-
18	2.09	2.46	2.12	-	-
22.5	1.21	1.18	1.18	0.93	1.09
Program and Set Numbers (Program-Set)			2-6	3-4	4-6

Batch number:	246-7					
Casting date:	7/26/2005					
Description:	24.4%-535-100% MG II-0.45					
Average Sample Depth (mm)	Chloride Concentration [Cl-] (lb/yd^3)					
Specimen	A	B	C	A-Repeat 1	B-Repeat 1	C-Repeat 1
2	9.63	10.38	10.59	-	-	-
6	7.24	7.65	6.90	-	-	-
11.5	5.08	5.68	4.71	-	-	-
18	3.22	3.03	2.57	-	-	-
22.5	1.98	2.02	1.39	1.49	1.49	1.11
Program and Set Numbers (Program-Set)			2-8	3-3	4-3	

Batch number:	246-14					
Casting date:	7/26/2005					
Description:	24.4%-535-100% MG II-0.45					
Average Sample Depth (mm)	Chloride Concentration [Cl-] (lb/yd^3)					
Specimen	D	E	F	D-Repeat 1	D-Repeat 2	E-Repeat 1
2	8.73	8.82	7.71	5.29†	8.54	-
6	6.19	6.19	5.70	-	-	-
11.5	3.65	4.83	3.25	-	-	-
18	2.51	2.32	1.61	-	-	-
22.5	1.36	1.27	0.73	1.18	-	1.11
Specimen	F-Repeat 1					
2	-					
6	-					
11.5	-					
18	-					
22.5	0.62					
Program and Set Numbers (Program-Set)			2-8	3-4	4-4	

Batch number:	328					
Casting date:	5/26/2006					
Description:	23.3%-535-60% G100-0.42					
Average Sample Depth (mm)	Chloride Concentration [Cl-] (lb/yd^3)					
Specimen	A	B	C	A-Repeat 1	B-Repeat 1	C-Repeat 1
2	13.20	11.90	13.94	12.27	11.59	10.10
6	4.89	5.08	5.45	-	-	4.96
11.5	1.80	1.86	1.86	-	-	-
18	0.62	0.81	0.87	-	-	-
22.5	0.28	0.50	0.59	-	-	0.62
Program and Set Numbers (Program-Set)			5-1	5-4		

Batch number:	330		
Casting date:	5/31/2006		
Description:	23.3%-583-100% I/II-0.36		
Average Sample Depth (mm)	Chloride Concentration [Cl-] (lb/yd^3)		
Specimen	A	B	C
2	11.44	11.18	11.15
6	6.75	6.10	6.03
11.5	2.32	1.98	1.95
18	0.44	0.44	0.60
22.5	0.31	0.25	0.28
Program and Set Numbers (Program-Set)			3-5

Batch number:	334		
Casting date:	6/1/2006		
Description:	23.3%-566-100% I/II-0.38		
Average Sample Depth (mm)	Chloride Concentration [Cl-] (lb/yd^3)		
Specimen	A	B	C
2	10.74	14.09	12.59
6	5.51	5.83	6.36
11.5	2.19	4.20†	2.60
18	0.63	1.00	0.85
22.5	0.31	0.44	0.31
Program and Set Numbers (Program-Set)			3-5

† Removed from analysis

Batch number:	335		
Casting date:	6/5/2006		
Description:	23.3%-550-100% I/II-0.40		
Average Sample Depth (mm)	Chloride Concentration [Cl-] (lb/yd^3)		
Specimen	A	B	C
2	12.84	11.72	10.84
6	6.62	7.56	5.50
11.5	3.97	3.50	3.03
18	1.47	1.16	0.94
22.5	0.44	0.50	0.37
Program and Set Numbers (Program-Set)			3-5

Batch number:	338					
Casting date:	6/7/2006					
Description:	23.3%-535-100% I/II-0.42					
Average Sample Depth (mm)	Chloride Concentration [Cl-] (lb/yd^3)					
Specimen	A	B	C	A-Repeat 1	C-Repeat 1	
2	14.27	11.97	13.21	-	-	
6	9.57	7.10	6.79	-	-	
11.5	2.74	3.12	3.09	-	2.31	
18	1.87	1.06	0.62	-	-	
22.5	1.12	0.44	0.31	0.65	-	
Program and Set Numbers (Program-Set)			1-1	3-5	5-1	5-2
			5-3	5-4	5-6	6-2
			7-2			

Batch number:	347				
Casting date:	6/21/2006				
Description:	23.2%-535-60% G120-0.42				
Average Sample Depth (mm)	Chloride Concentration [Cl-] (lb/yd^3)				
Specimen	A	B	C		
2	16.54	18.06	12.42		
6	9.37	8.81	6.18		
11.5	2.79	2.55	2.02		
18	1.02	1.49	1.06		
22.5	0.87	0.93	0.99		
Program and Set Numbers (Program-Set)			1-3	5-1	5-2

Batch number:	351				
Casting date:	6/27/2006				
Description:	21.6%-497-60% G120-0.42				
Average Sample Depth (mm)	Chloride Concentration [Cl-] (lb/yd^3)				
Specimen	A	B	C	A-Repeat 1	B-Repeat 1
2	11.42	10.80†	14.23		11.98†
6	6.90	11.36†	6.74	7.43	12.20†
11.5	2.81	5.99†	2.00		6.43†
18	1.53	1.37†	1.00		1.56†
22.5	1.06	0.75†	0.81		0.94†
Program and Set Numbers (Program-Set)			1-3	5-5	5-6

† Removed from analysis

Batch number:	354		
Casting date:	6/30/2006		
Description:	21.6%-497-60% G120 6% SF-0.42		
Average Sample Depth (mm)	Chloride Concentration [Cl-] (lb/yd^3)		
Specimen	A	B	C
2	-	10.90	11.58
4	9.09	-	-
6	-	4.05	4.23
8.5	3.67	-	-
11.5	-	1.18	2.30
14.5	1.37	-	-
18	-	0.81	1.37
22.5	-	0.81	1.31
Program and Set Numbers (Program-Set)			1-4 / 5-5

Batch number:	**355**				
Casting date:	7/7/2006				
Description:	20.5%-460-60% G120 6% SF-0.42				
Average Sample Depth (mm)	**Chloride Concentration [Cl-] (lb/yd^3)**				
Specimen	**A**	**B**	**C**	**B-Repeat 1**	**C-Repeat 1**
2	9.56	11.56	7.12		10.81
6	3.87	0.81†	3.19	4.12	4.25
11.5	1.25	1.31	1.12		1.03
14.5	0.91	-	-		-
18	-	0.75	0.94		-
22.5	0.69	0.75	0.81		1.06
Program and Set Numbers (Program-Set)			1-4	5-6	

† Removed from analysis

Batch number:	**358**			
Casting date:	7/19/2006			
Description:	20.5%-460-80% G120 6% SF-0.42			
Average Sample Depth (mm)	**Chloride Concentration [Cl-] (lb/yd^3)**			
Specimen	**A**	**B**	**C**	**C-Repeat 1**
2	9.43	9.86	6.27	
6	4.18	5.06	2.93	
11.5	1.56	1.69	1.44	
18	1.00	0.91	0.66	1.31
22.5	0.87	1.25	1.09	1.12
Program and Set Numbers (Program-Set)			5-6	

Batch number:	378					
Casting date:	11/3/2006					
Description:	23.3%535-60% G100 6% SF-0.42					
Average Sample Depth (mm)	Chloride Concentration [Cl-] (lb/yd^3)					
Specimen	A	B	C	A-Repeat 1	B-Repeat 1	C-Repeat 1
2	8.04	6.06	4.89	6.40	5.01	6.96
6	4.21	2.84	2.04	-	2.41	3.53
11.5	1.61	0.99	0.56	-	1.18	0.56
18	0.87	0.62	0.43	0.43	0.49	-
22.5	0.93	0.62	0.40	-	0.40	-
Program and Set Numbers (Program-Set)			5-4			

Batch number:	380		
Casting date:	11/13/2006		
Description:	23.3%-535-6% SF-0.42		
Average Sample Depth (mm)	Chloride Concentration [Cl-] (lb/yd^3)		
Specimen	A	B	C
2	13.43	13.62	13.56
6	7.59	8.08	8.15
11.5	2.61	3.61	2.92
18	0.50	1.06	0.44
22.5	0.37	0.50	0.31
Program and Set Numbers (Program-Set)			5-3

Batch number:	**381**			
Casting date:	11/14/2006			
Description:	23.3%-535-3% SF-0.42			
Average Sample Depth (mm)	**Chloride Concentration [Cl-] (lb/yd^3)**			
Specimen	**A**	**B**	**C**	**A-Repeat 1†**
2	12.67	11.27	10.15	8.96
6	7.41	7.16	7.72	4.05
11.5	3.73	3.30	3.05	1.80
18	1.06	0.87	0.68	0.16
22.5	0.50	0.62	0.31	0.37
Program and Set Numbers (Program-Set)		5-3		

Batch number:	**385**		
Casting date:	11/27/2006		
Description:	23.3%-535-100% I/II-0.42-1% SRA		
Average Sample Depth (mm)	**Chloride Concentration [Cl-] (lb/yd^3)**		
Specimen	**A**	**B**	**C**
2	9.17	7.40	10.57
6	5.16	5.47	6.59
11.5	2.61	2.86	3.27
18	0.44	0.93	0.93
22.5	0.25	0.31	0.37
Program and Set Numbers (Program-Set)		6-2	

Batch number:	**387**		
Casting date:	11/29/2006		
Description:	26.9%-602-100% I/II-0.44-KDOT		
Average Sample Depth (mm)	**Chloride Concentration [Cl-] (lb/yd^3)**		
Specimen	**A**	**B**	**C**
2	9.25	10.75	10.94
6	6.81	7.13	6.88
11.5	3.75	4.19	3.88
18	1.13	1.19	1.25
22.5	0.44	0.50	0.38
Program and Set Numbers (Program-Set)		7-2	

Batch number:	**388**			
Casting date:	12/13/2006			
Description:	21.6%-497-100% I/II-0.42			
Average Sample Depth (mm)	**Chloride Concentration [Cl-] (lb/yd^3)**			
Specimen	**A**	**B**	**C**	
2	10.95	14.71	11.95	
6	7.20	9.23	8.01	
11.5	4.38	5.82	4.44	
18	1.63	2.25	1.25	
22.5	0.69	0.75	0.56	
Program and Set Numbers (Program-Set)			5-5	5-6

Batch number:	**424**					
Casting date:	1/23/2007					
Description:	23.3%-535-30% G120-0.42					
Average Sample Depth (mm)	**Chloride Concentration [Cl-] (lb/yd^3)**					
Specimen	**A**	**B**	**C**	**A-Repeat 1**	**A-Repeat 2**	**B-Repeat 1**
2	15.76	6.78	9.79	12.52	-	-
4	10.75	-	-	-	-	-
6	NA††	3.61	4.54	-	-	-
8.5	6.22	-	-	-	-	-
11.5	3.76	1.99	1.12	-	-	-
18	0.50	0.56	0.31	0.31	0.68	0.81
22.5	0.62	0.37	0.44	0.19	0.84	0.68
Specimen	**B-Repeat 2**	**C-Repeat 1**	**C-Repeat 2**	**C-Repeat 3**		
2	11.78	11.00	-	17.83†	-	-
4	-	-	-	-	-	-
6	6.04	5.35	-	11.38†	-	-
8.5	-	-	-	5.00†	-	-
11.5	2.80	0.81	0.84	1.99†	-	-
18	0.99	-	-	0.53†	-	-
22.5	-	0.50	-	0.62	-	-
Program and Set Numbers (Program-Set)			5-2			

† Removed from analysis

†† Not available

Batch number:	**520**		
Casting date:	3/18/2008		
Description:	24.4%-535-100% I/II-0.45-2% SRA		
Average Sample Depth (mm)	**Chloride Concentration [Cl-] (lb/yd^3)**		
Specimen	**A**	**B**	**C**
2	6.42	6.05	6.55
6	5.07	5.13	5.56
11.5	3.09	3.34	3.89
18	1.05	1.17	1.30
22.5	0.37	0.43	0.43
Program and Set Numbers (Program-Set)			6-1

Table B.2 Drying time between deponding and lathe sampling

Batch	Casting Date	Time From Casting to Deponding, a	Lathe Sampling Date			Time From Casting to Sampling by Lathe, dt		
		Days	A	B	C	Days	Days	Days
131	6/21/2004	125	12/10/2004	12/10/2004	12/13/2004	172	172	175
133	6/22/2004	125	12/13/2004	12/14/2004	12/14/2004	174	175	175
139	6/24/2004	125	12/14/2004	12/15/2004	12/16/2004	173	174	175
141	6/25/2004	125	12/17/2004	12/17/2004	12/17/2004	175	175	175
144	6/26/2004	125	1/13/2005	1/14/2005	1/17/2005	201	202	205
146	6/28/2004	125	1/17/2005	1/17/2005	1/18/2005	203	203	204
148	6/29/2004	125	1/18/2005	1/19/2005	1/19/2005	203	204	204
161	7/14/2004	132	NR	NR	NR	-	-	-
164-7	7/21/2004	125	2/28/2005	3/16/2005	3/20/2005	222	238	242
14-14	7/21/2004	132	3/20/2005	3/21/2005	NR	242	243	-
164-28	7/21/2004	146	NR	NR	NR	-	-	-
234-7	6/27/2005	125	3/21/2006	3/17/2006	5/23/2006	267	263	330
234-14	6/27/2005	132	6/6/2006	6/52006	6/15006	344	343	353
235-7	6/30/2005	125	6/82006	6/13/2006	6/16/2006	343	348	351
235-14	6/30/2005	132	6/14/2006	6/16/2006	6/16/2006	349	351	351
239-7	7/8/2005	125	6/19/2006	6/19/2006	6/19/2006	346	346	346
239-14	7/8/2005	132	6/21/2006	6/21/2006	6/22/2006	348	348	349
240-7	7/13/2005	125	6/9/2006	6/13/2006	6/17/2006	331	335	339
240-14	7/13/2005	123	6/26/2006	6/26/2006	6/28/2006	348	348	350
244-7	7/20/2005	125	6/28/2006	6/28/2006	6/29/2006	343	-	344
244-14	7/20/2005	132	6/30/2006	6/30/2006	6/30/2006	345	343	345
246-7	7/26/2005	125	7/2/2006	7/3/2006	7/3/2006	341	345	342
246-14	7/26/2005	132	6/22/2006	6/23/2006	6/23/2006	331	342	332
328	5/26/2006	132	12/4/2006	12/11/2006	12/18/2006	192	332	206
330	5/31/2006	132	12/18/2006	12/19/2006	12/19/2006	201	199	202
334	6/1/2006	132	12/20/2006	12/21/2006	12/20/2006	202	202	202
335	6/5/2006	132	12/22/2006	12/25/2006	1/1/2007	200	203	225
338	6/7/2006	132	1/17/2007	1/18/2007	2/1/2007	224	225	239
347	6/21/2006	132	1/23/2007	1/24/2007	1/30/2007	216	217	223
351	6/27/2006	132	2/5/2007	2/6/2007	2/7/2007	223	224	225
354	6/30/2006	132	2/12/2007	2/14/2007	2/19/2007	227	229	234
355	7/5/2006	132	2/28/2007	2/27/2007	2/21/2007	238	237	231
358	7/19/2006	133	3/7/2007	3/8/2007	3/14/2007	231	232	238
378	11/3/2006	135	4/17/2007	4/20/2007	NR	165	168	-
380	11/13/2006	132	4/10/2007	5/21/2007	4/12/2007	148	189	150
381	11/14/2006	132	5/21/2007	5/22/2007	5/23/2007	188	189	190
385	11/27/2006	132	5/29/2007	5/30/2007	5/31/2007	183	184	185
387	11/29/2006	132	6/4/2007	6/4/2007	6/7/2007	187	187	190
388	12/13/2006	132	NR	6/13/2007	6/14/2007	-	182	183
424	1/23/2007	132	6/20/2007	6/25/2007	6/26/2007	148	153	154
520								

NR = Not Reported

Table B.2 (cont.) Drying time between deponding and lathe sampling

Batch	Average dt	Time From Deponding to Sampling, dt-a	Group Average
	Days	Days	Days
131	173	48	
133	175	50	
139	174	49	
141	175	50	
144	203	78	
146	203	78	
148	204	79	
161	-	-	
164-7	234	109	
14-14	243	111	
164-28	-	-	72
234-7	287	162	
234-14	347	215	
235-7	347	222	
235-14	350	218	
239-7	346	221	
239-14	348	216	
240-7	335	210	
240-14	349	217	
244-7	343	218	
244-14	345	213	
246-7	342	217	
246-14	332	200	211
328	199	67	
330	202	70	
334	202	70	
335	209	77	
338	229	97	
347	219	87	
351	224	92	
354	230	98	
355	235	103	
358	234	101	
378	167	32	
380	162	30	
381	189	57	
385	184	52	
387	188	56	
388	183	51	
424	152	20	
520			68

NR = Not Reported

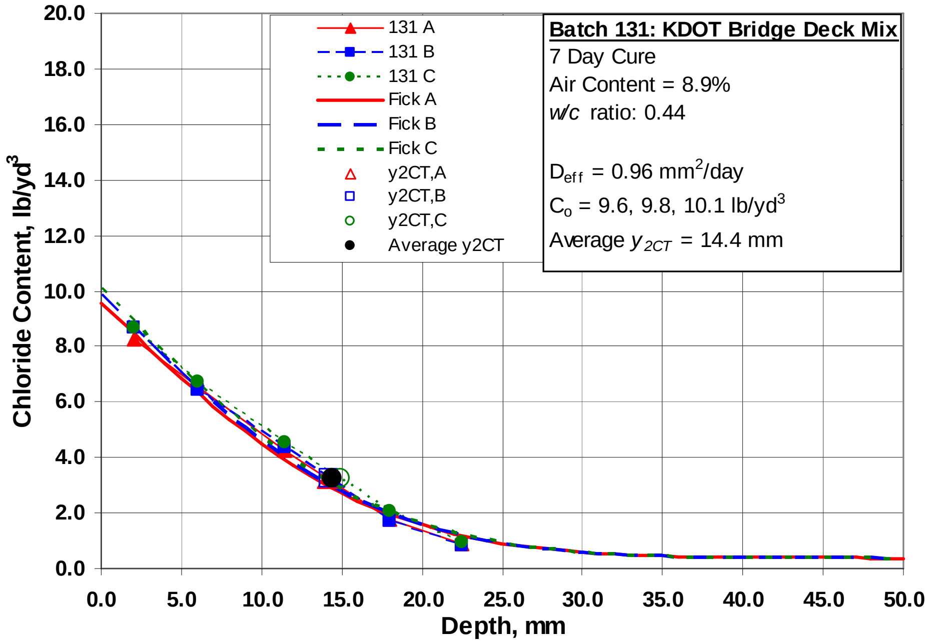


Fig. B.1 Permeability - individual chloride profiles and y_{2CT} for Batch 131 with 26.9% paste, 602 CF, 100% Type I/II cement, 0.44 *w/c*, 7-day cure, KDOT bridge subdeck mix.

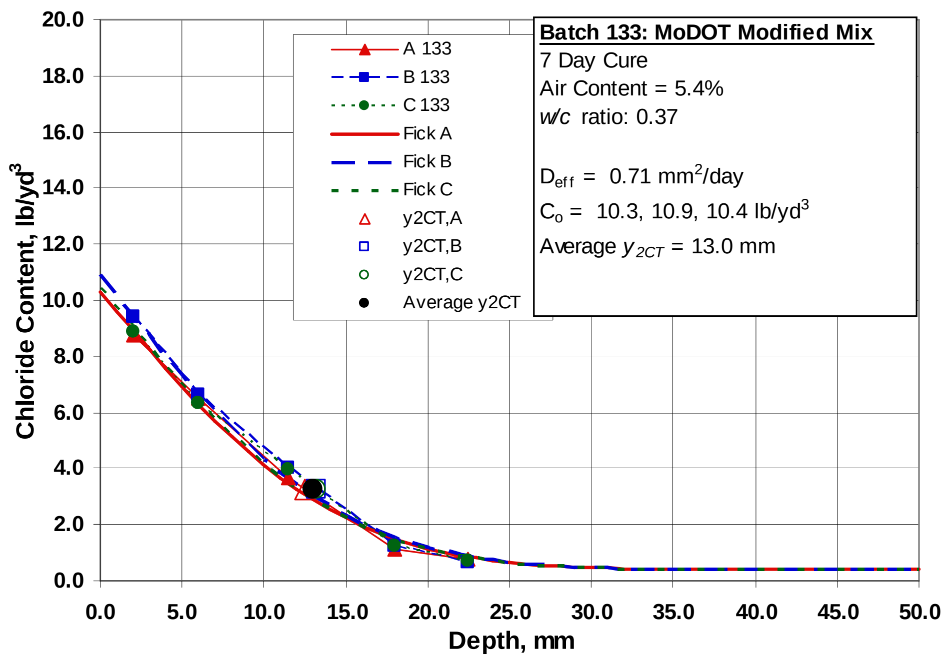


Fig. B.2 Permeability - individual chloride profiles and y_{2CT} for Batch 133 with 29.6% paste, 729 CF, 100% Type I/II cement, 0.37 *w/c*, 7-day cure, MoDOT modified bridge deck mix.

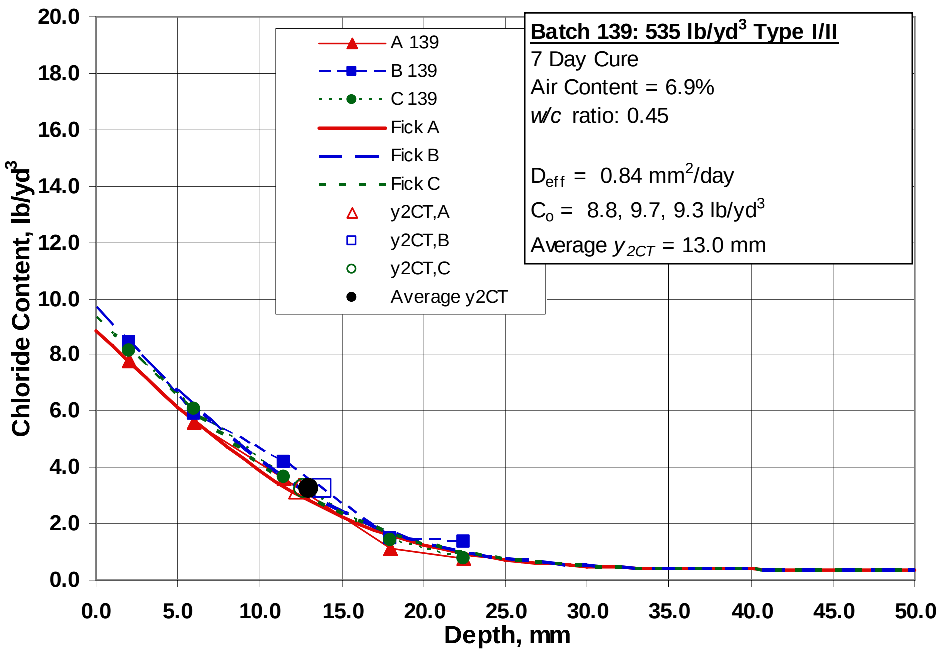


Fig. B.3 Permeability - individual chloride profiles and y_{2CT} for Batch 139 with 24.2% paste, 535 CF, 100% Type I/II cement, 0.45 *w/c*, 7-day cure.

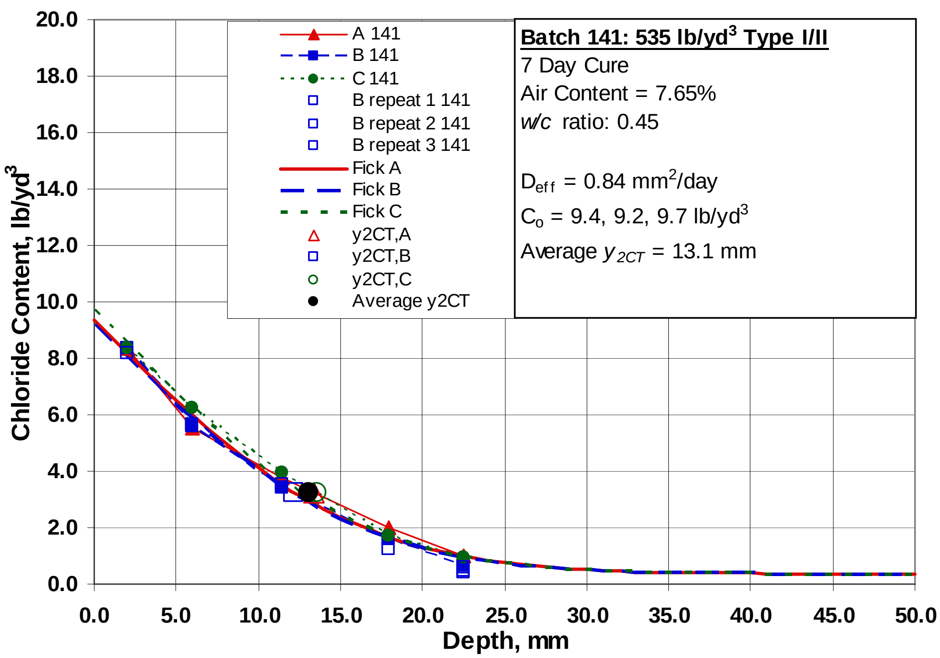


Fig. B.4 Permeability - individual chloride profiles and y_{2CT} for Batch 141 with 24.2% paste, 535 CF, 100% Type I/II cement, 0.45 *w/c*, 7-day cure.

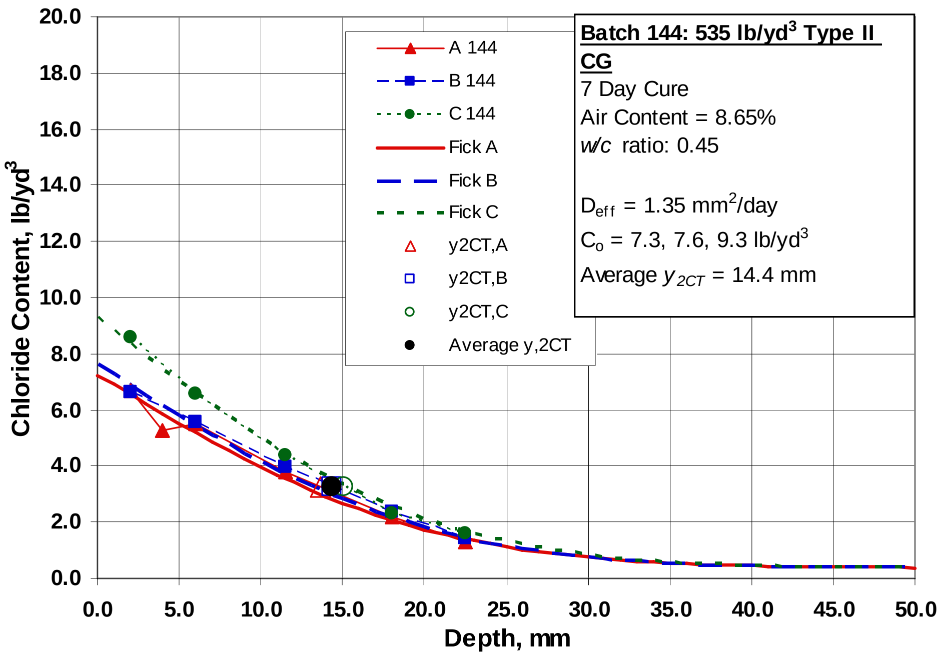


Fig. B.5 Permeability - individual chloride profiles and y_{2CT} for Batch 144 with 24.2% paste, 535 CF, 100% coarse ground Type II cement, 0.45 *w/c*, 7-day cure.

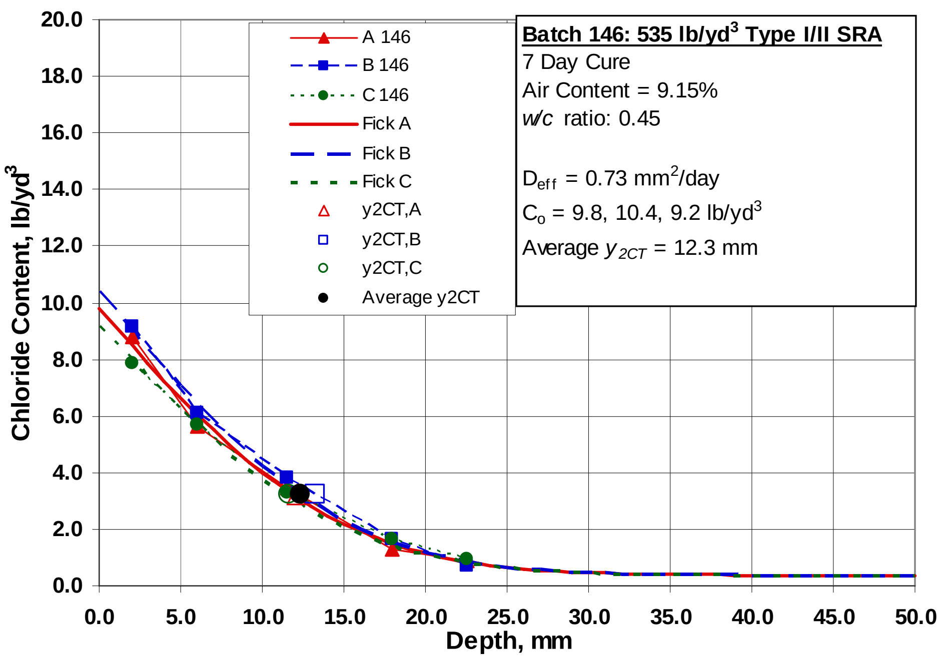


Fig. B.6 Permeability - individual chloride profiles and y_{2CT} for Batch 146 with 24.2% paste, 535 CF, 100% Type I/II cement, 0.45 *w/c*, 7-day cure, 2% SRA.

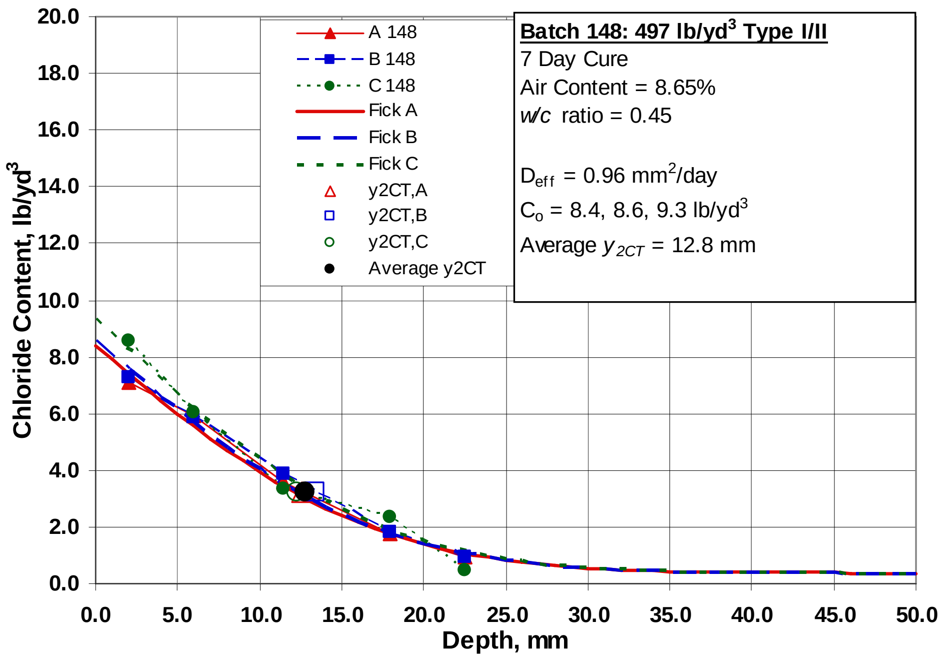


Fig. B.7 Permeability - individual chloride profiles and y_{2CT} for Batch 148 with 22.5% paste, 497 CF, 100% Type I/II cement, 0.45 *w/c*, 7-day cure.

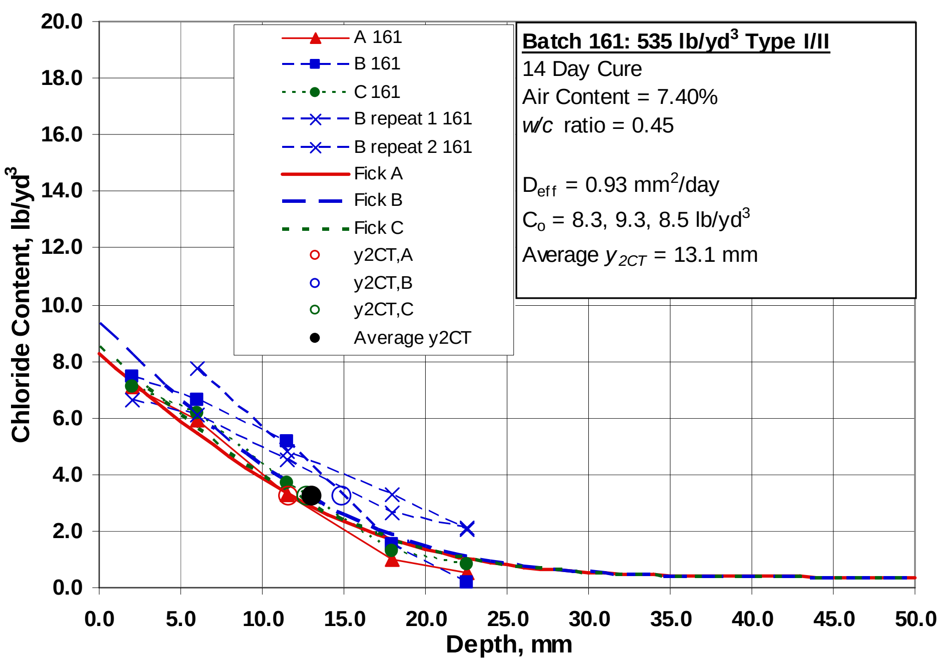


Fig. B.8 Permeability - individual chloride profiles and y_{2CT} for Batch 161 with 24.2% paste, 535 CF, 100% Type I/II cement, 0.45 *w/c*, 14-day cure.

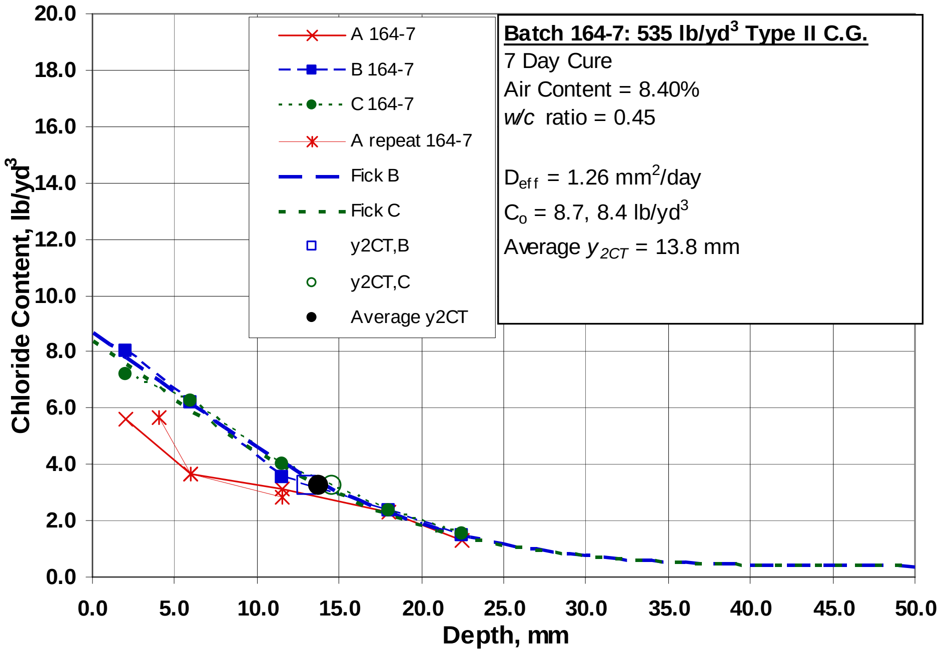


Fig. B.9 Permeability - individual chloride profiles and y_{2CT} for Batch 164-7 with 24.2% paste, 535 CF, 100% coarse ground Type II cement, 0.45 *w/c*, 7-day cure.

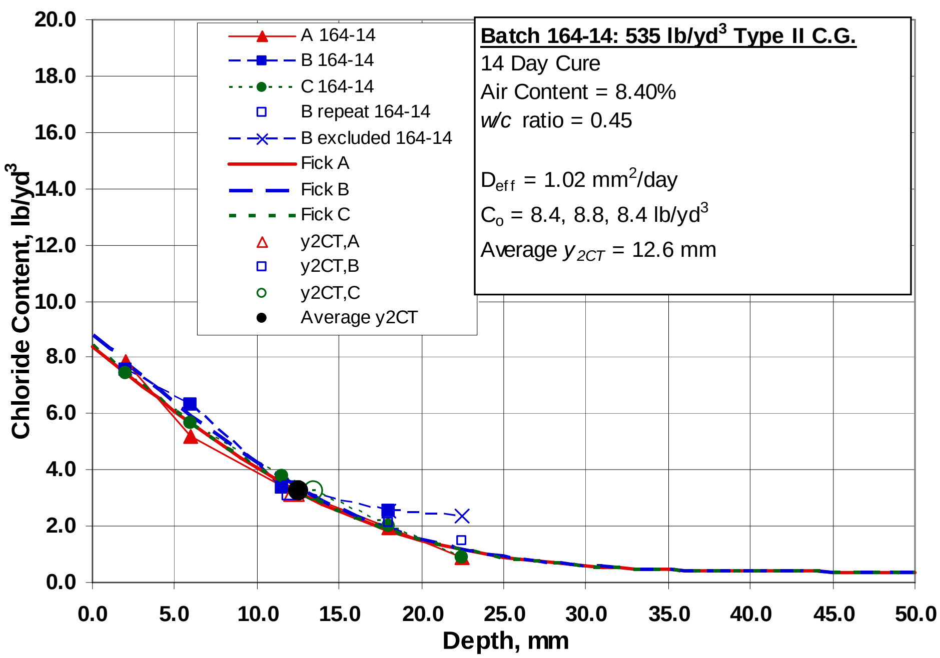


Fig. B.10 Permeability - individual chloride profiles and y_{2CT} for Batch 164-14 with 24.2% paste, 535 CF, 100% coarse ground Type II cement, 0.45 *w/c*, 28-day cure.

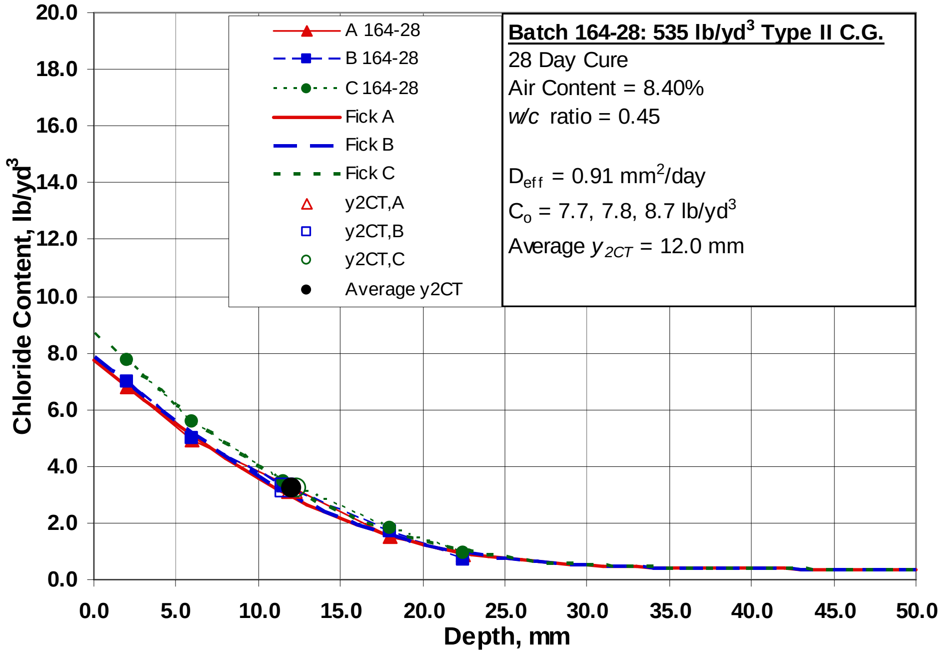


Fig. B.11 Permeability - individual chloride profiles and y_{2CT} for Batch 164-28 with 24.2% paste, 535 CF, 100% coarse ground Type II cement, 0.45 *w/c*, 28-day cure.

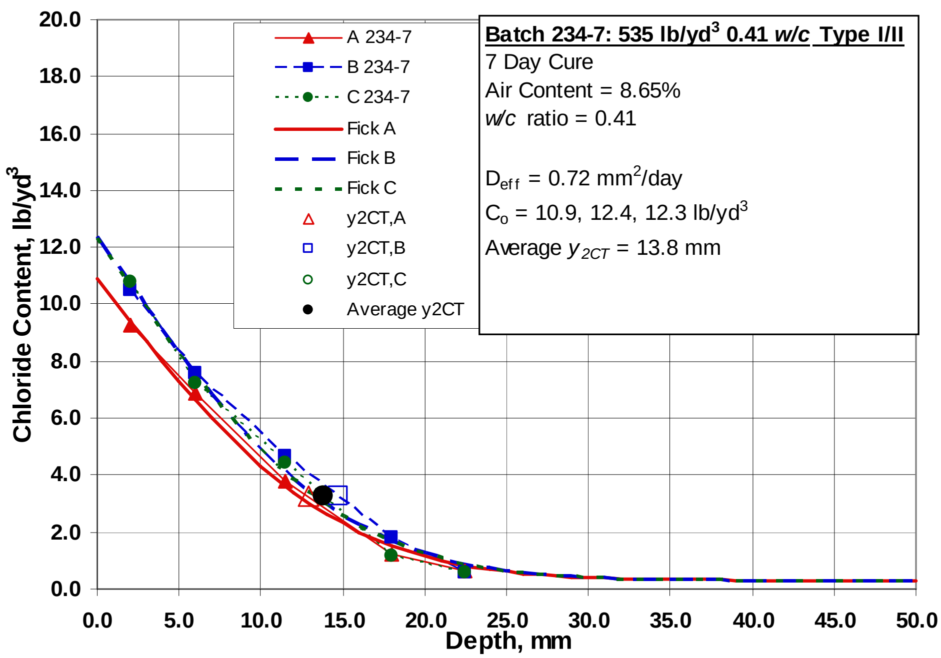


Fig. B.12 Permeability - individual chloride profiles and y_{2CT} for Batch 234-7 with 23.1% paste, 535 CF, 100% Type I/II cement, 0.41 *w/c*, 7-day cure.

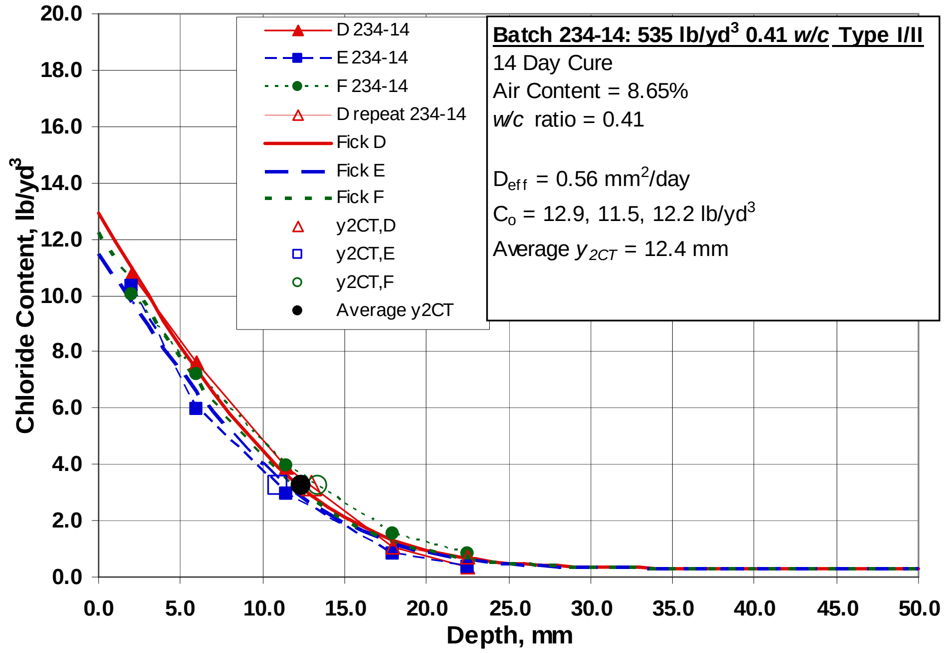


Fig. B.13 Permeability - individual chloride profiles and y_{2CT} for Batch 234-14 with 23.1% paste, 535 CF, 100% Type I/II cement, 0.41 *w/c*, 14-day cure.

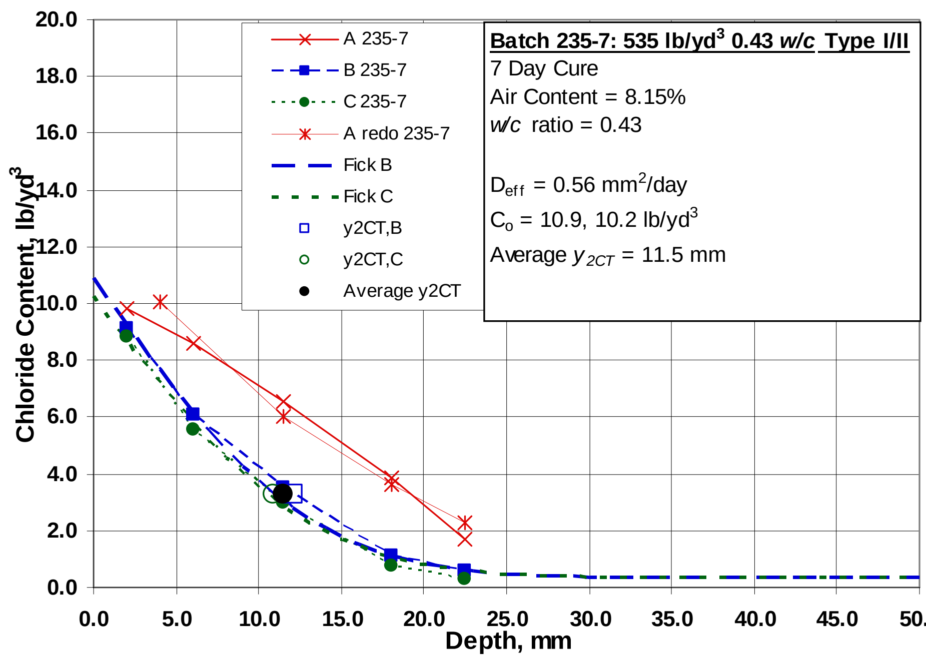


Fig. B.14 Permeability - individual chloride profiles and y_{2CT} for Batch 235-7 with 23.7% paste, 535 CF, 100% Type I/II cement, 0.43 *w/c*, 7-day cure.

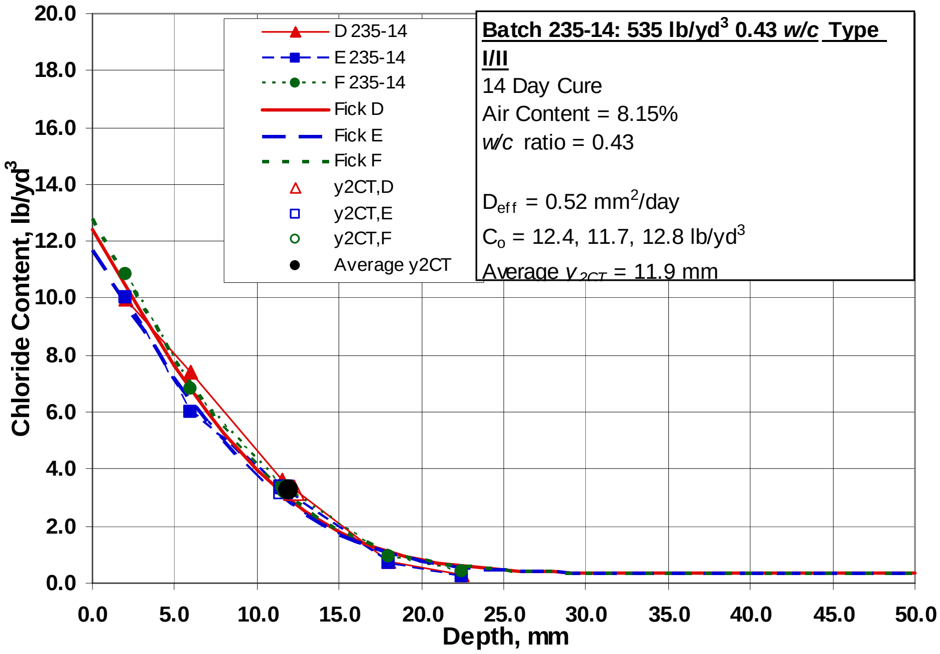


Fig. B.15 Permeability - individual chloride profiles and y_{2CT} for Batch 235-14 with 23.7% paste, 535 CF, 100% Type I/II cement, 0.43 *w/c*, 14-day cure.

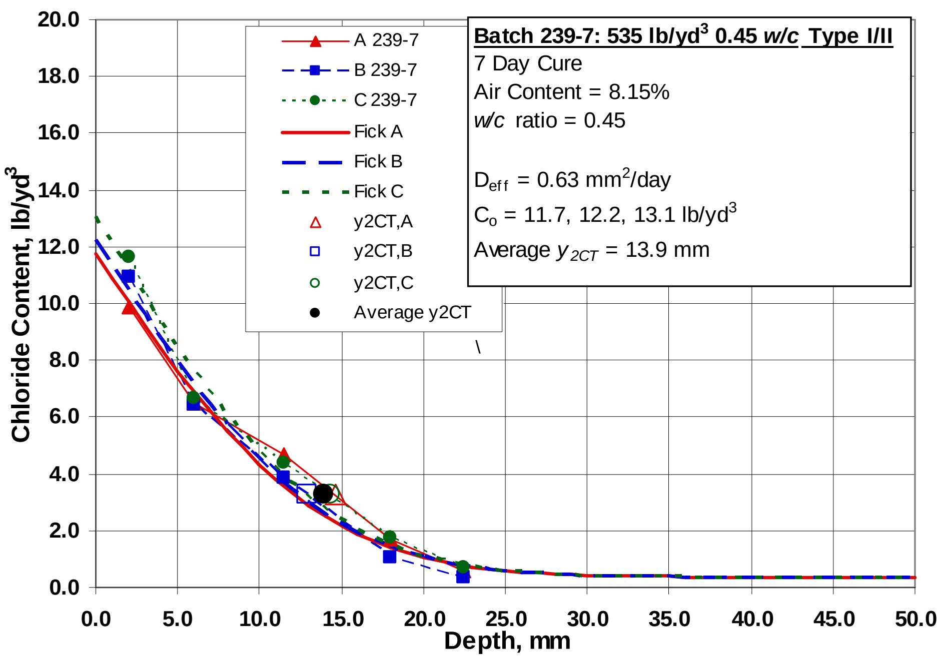


Fig. B.16 Permeability - individual chloride profiles and y_{2CT} for Batch 239-7 with 24.4% paste, 535 CF, 100% Type I/II cement, 0.45 *w/c*, 7-day cure.

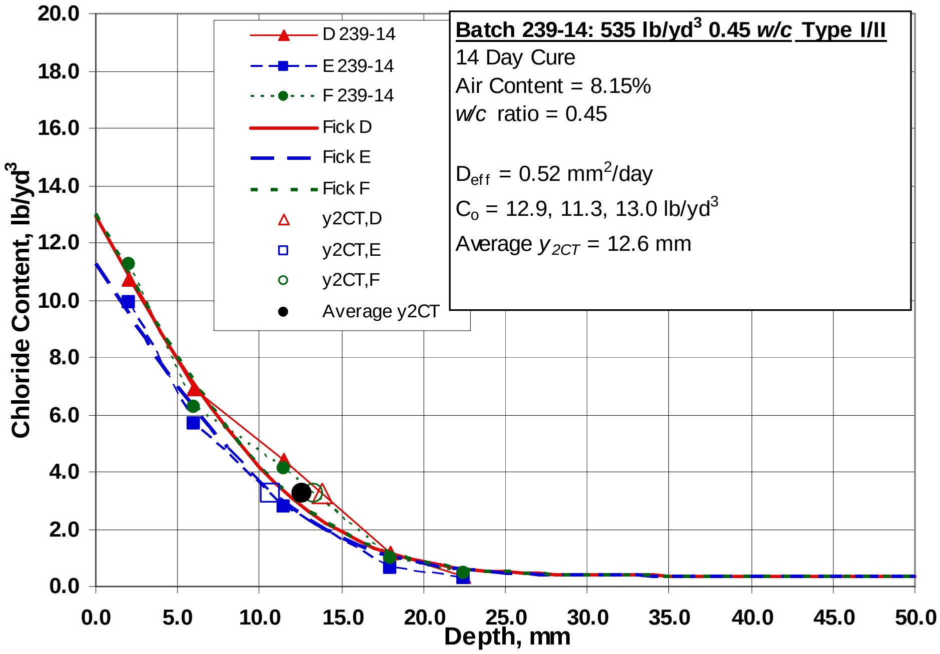


Fig. B.17 Permeability - individual chloride profiles and y_{2CT} for Batch 239-14 with 24.4% paste, 535 CF, 100% Type I/II cement, 0.45 *w/c*, 14-day cure.

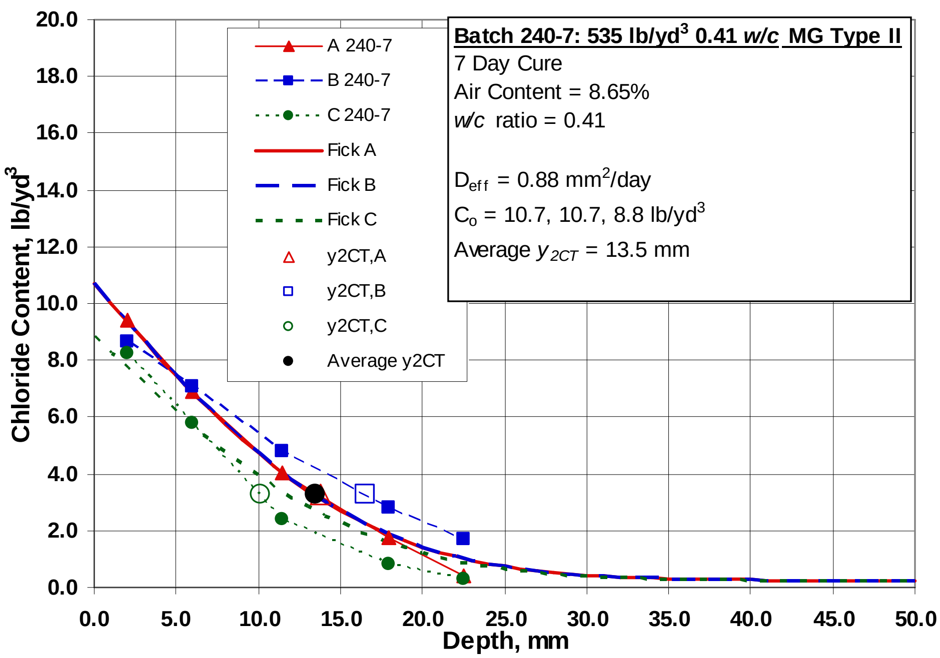


Fig. B.18 Permeability - individual chloride profiles and y_{2CT} for Batch 240-7 with 23.1% paste, 535 CF, 100% medium ground Type II cement, 0.41 *w/c*, 7-day cure.

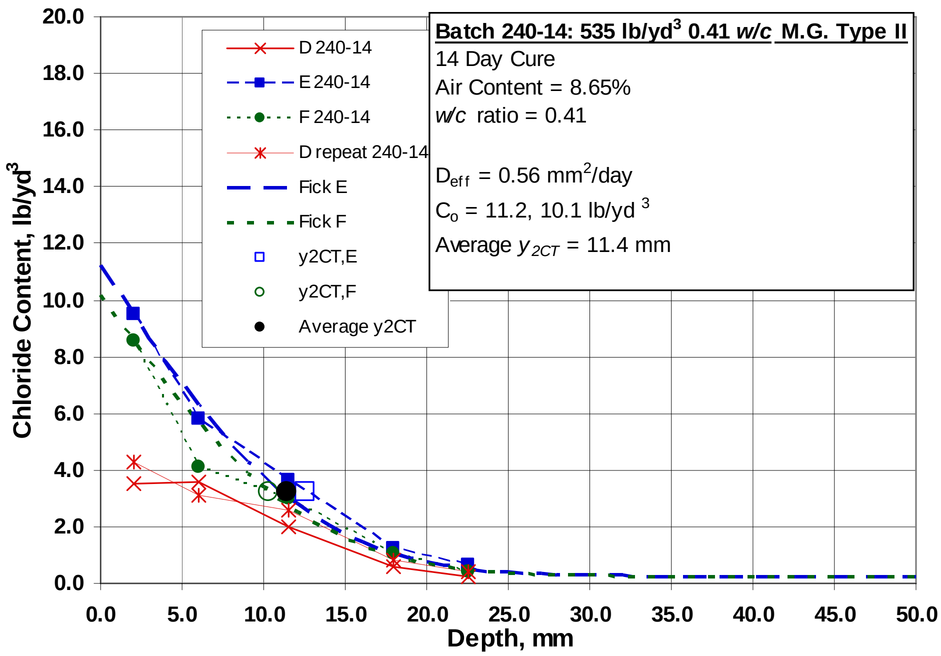


Fig. B.19 Permeability - individual chloride profiles and y_{2CT} for Batch 240-14 with 23.1% paste, 535 CF, 100% medium ground Type II cement, 0.41 *w/c*, 14-day cure.

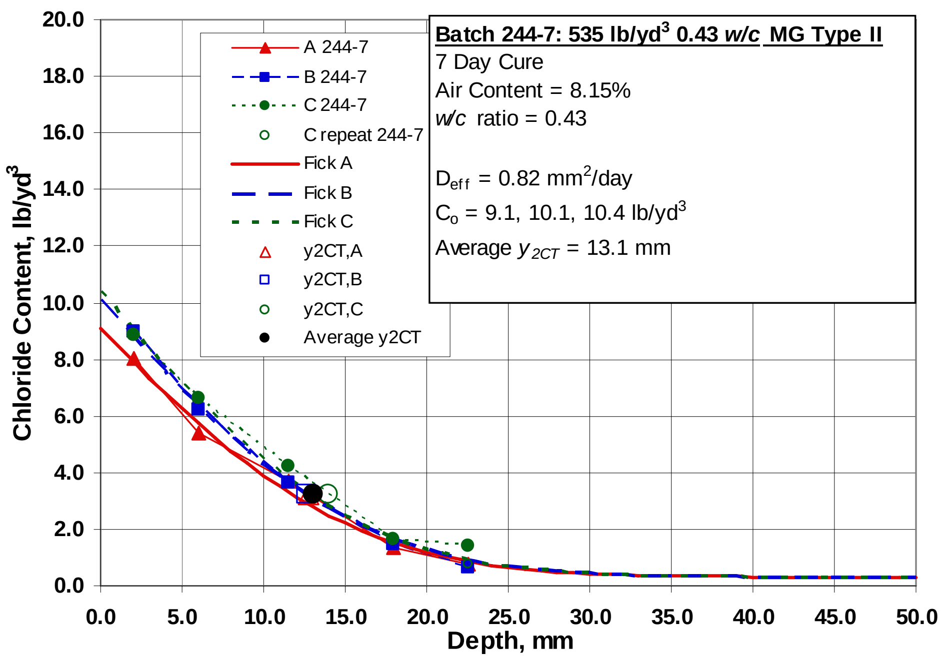


Fig. B.20 Permeability - individual chloride profiles and y_{2CT} for Batch 244-7 with 23.7% paste, 535 CF, 100% medium ground Type II cement, 0.43 *w/c*, 7-day cure.

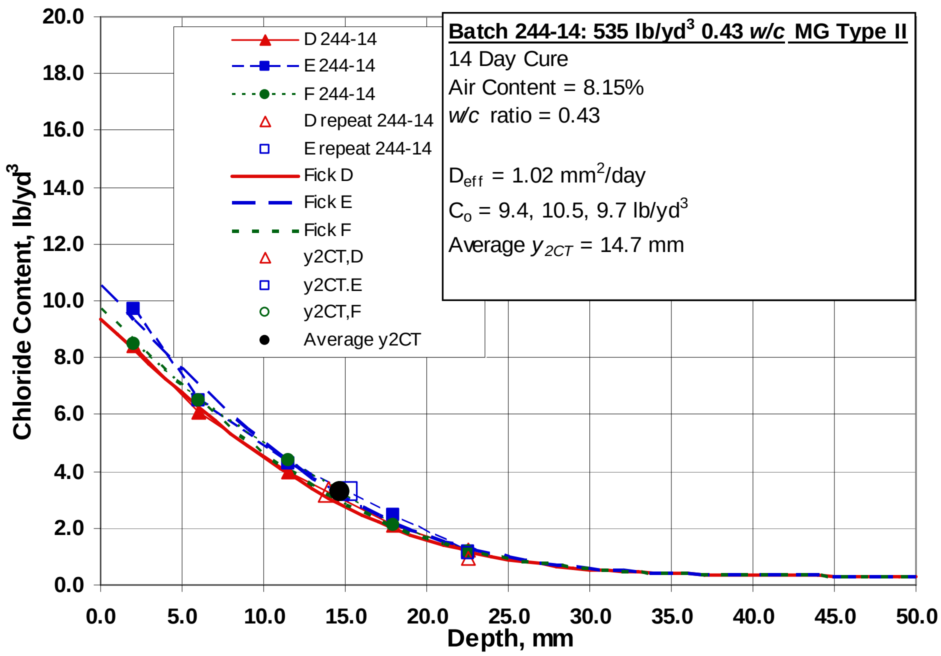


Fig. B.21 Permeability - individual chloride profiles and y_{2CT} for Batch 244-14 with 23.7% paste, 535 CF, 100% medium ground Type II cement, 0.43 *w/c*, 14-day cure.

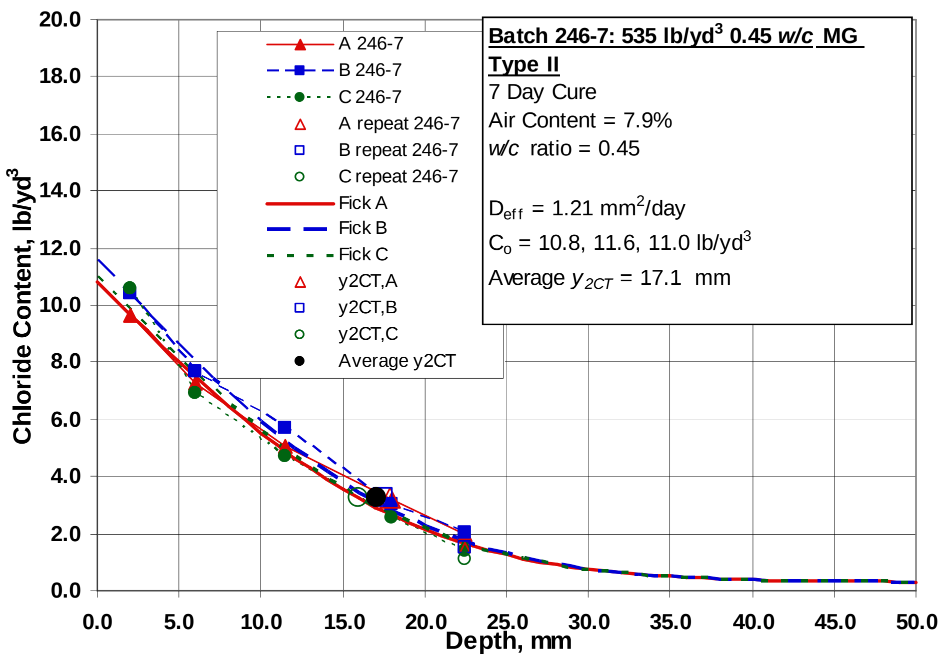


Fig. B.22 Permeability - individual chloride profiles and y_{2CT} for Batch 246-7 with 24.4% paste, 535 CF, 100% medium ground Type II cement, 0.45 *w/c*, 7-day cure.

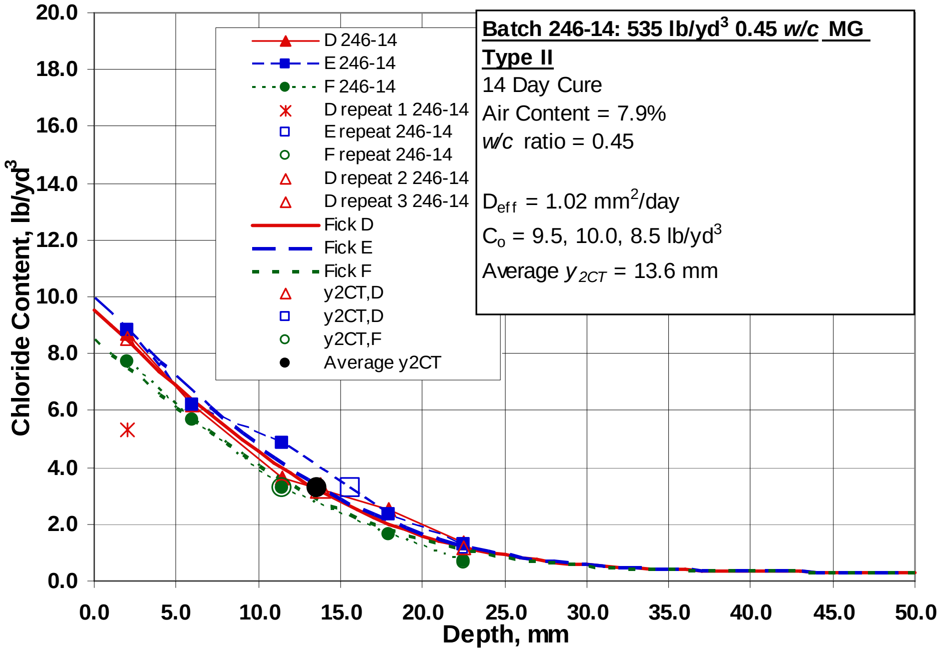


Fig. B.23 Permeability - individual chloride profiles and y_{2CT} for Batch 246-14 with 24.4% paste, 535 CF, 100% medium ground Type II cement, 0.45 *w/c*, 14-day cure.

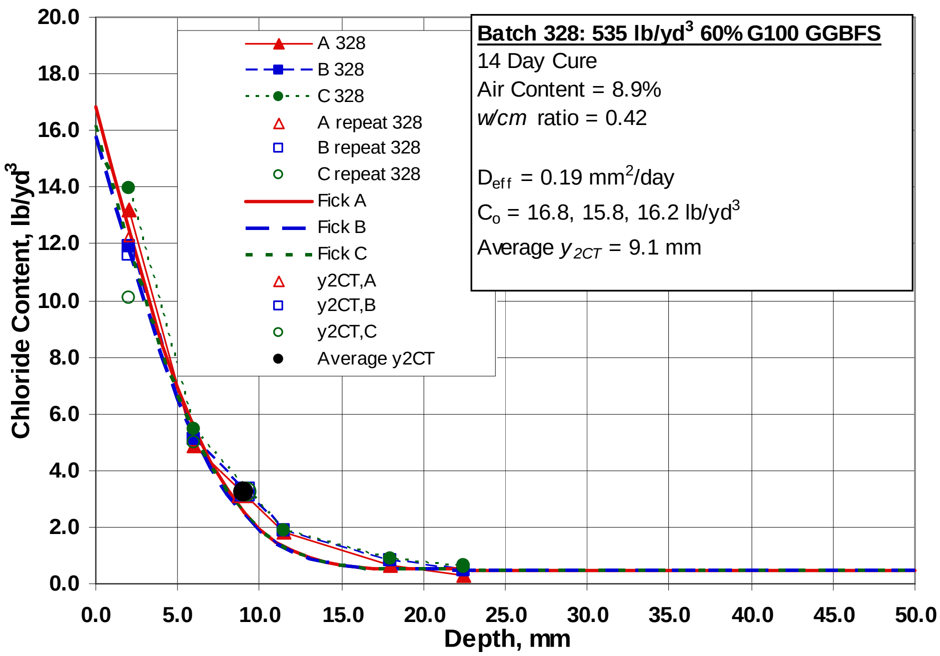


Fig. B.24 Permeability - individual chloride profiles and y_{2CT} for Batch 328 with 23.3% paste, 535 CF, 60% G100, 0.42 *w/cm*, 14-day cure.

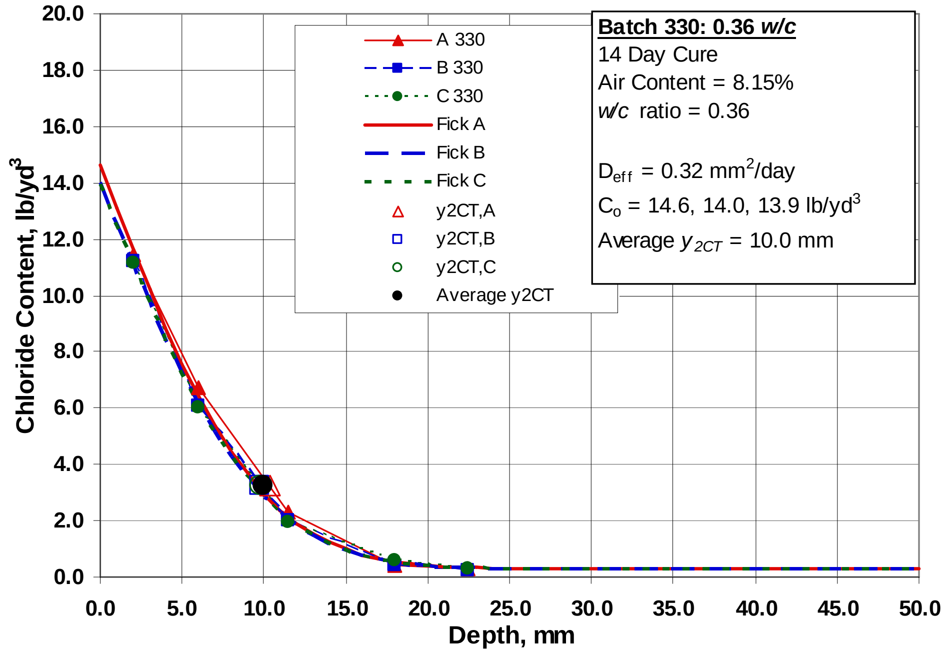


Fig. B.25 Permeability - individual chloride profiles and y_{2CT} for Batch 330 with 23.3% paste, 583 CF, 100% Type I/II cement, 0.36 *w/c* 14-day cure.

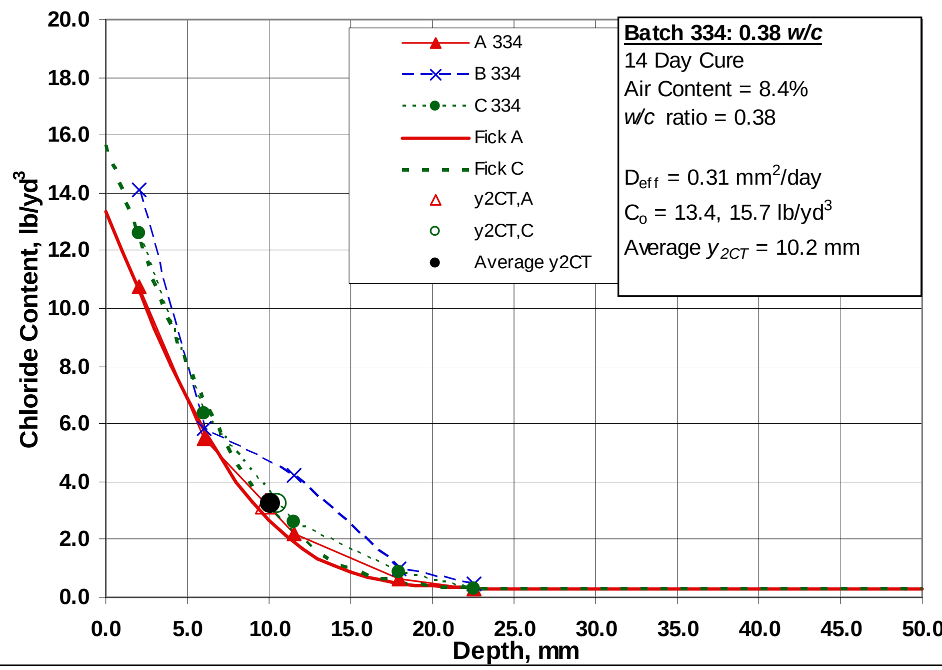


Fig. B.26 Permeability - individual chloride profiles and y_{2CT} for Batch 334 with 23.3% paste, 566 CF, 100% Type I/II cement, 0.38 *w/c*, 14-day cure.

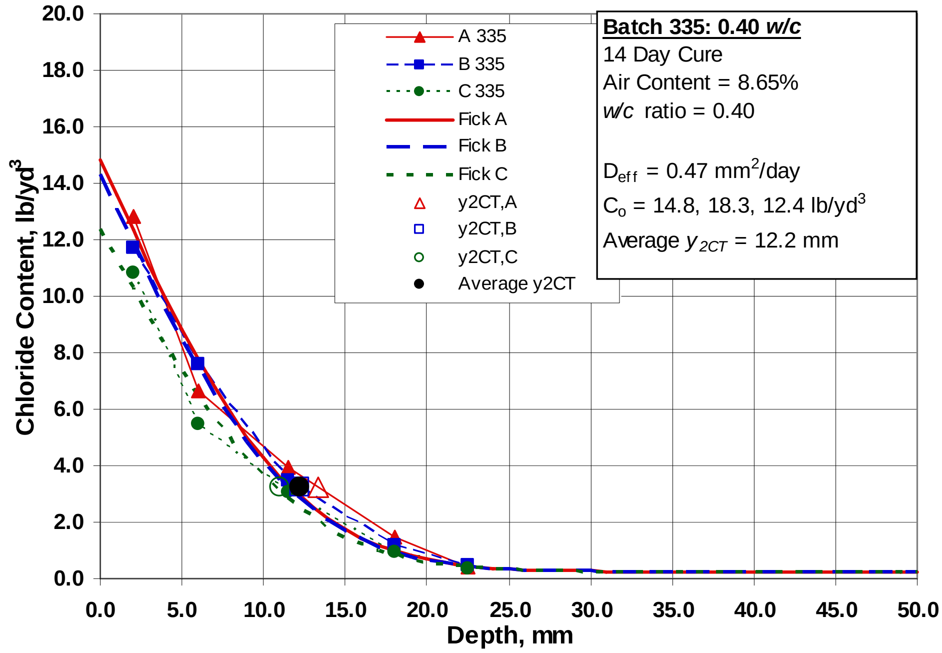


Fig. B.27 Permeability - individual chloride profiles and y_{2CT} for Batch 335 with 23.2% paste, 550 CF, 100% Type I/II cement, 0.40 *w/c*, 14-day cure.

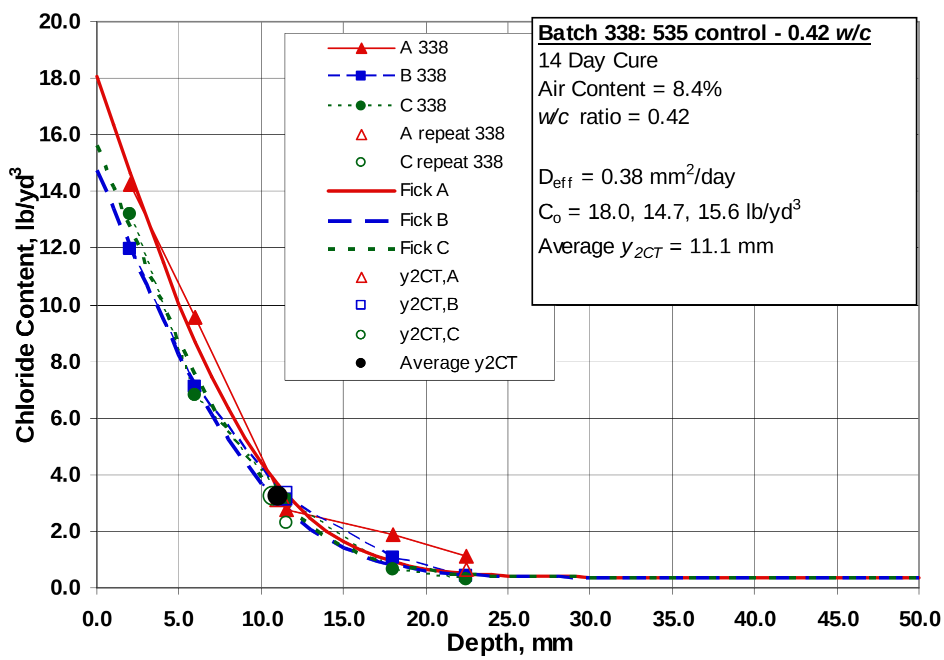


Fig. B.28 Permeability - individual chloride profiles and y_{2CT} for Batch 338 with 23.3% paste, 535 CF, 100% Type I/II cement, 0.42 *w/c*, 14-day cure.

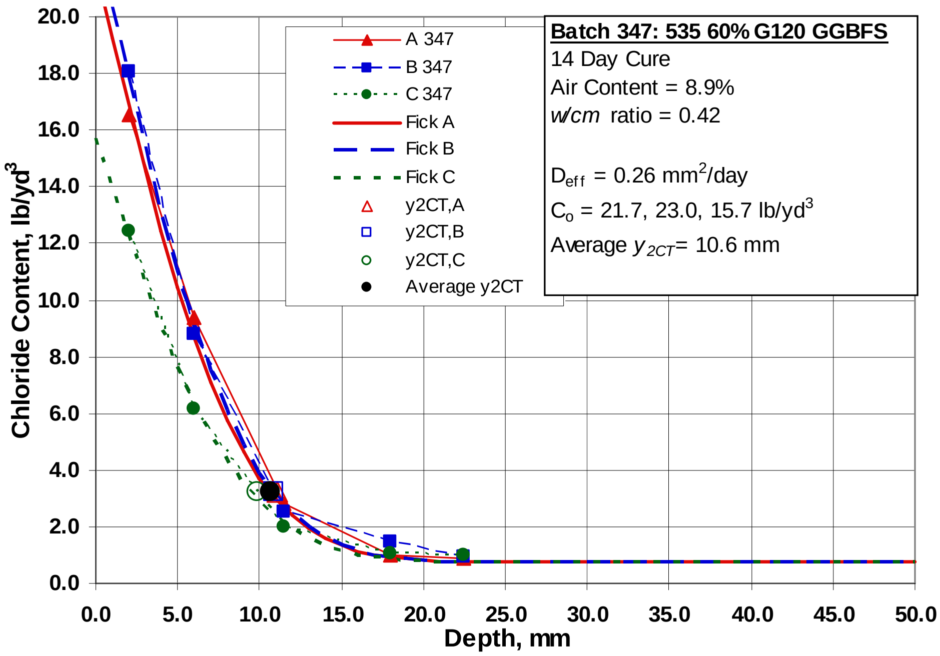


Fig. B.29 Permeability - individual chloride profiles and y_{2CT} for Batch 347 with 23.2% paste, 535 CF, 60% G120, 0.42 *w/cm*, 14-day cure.

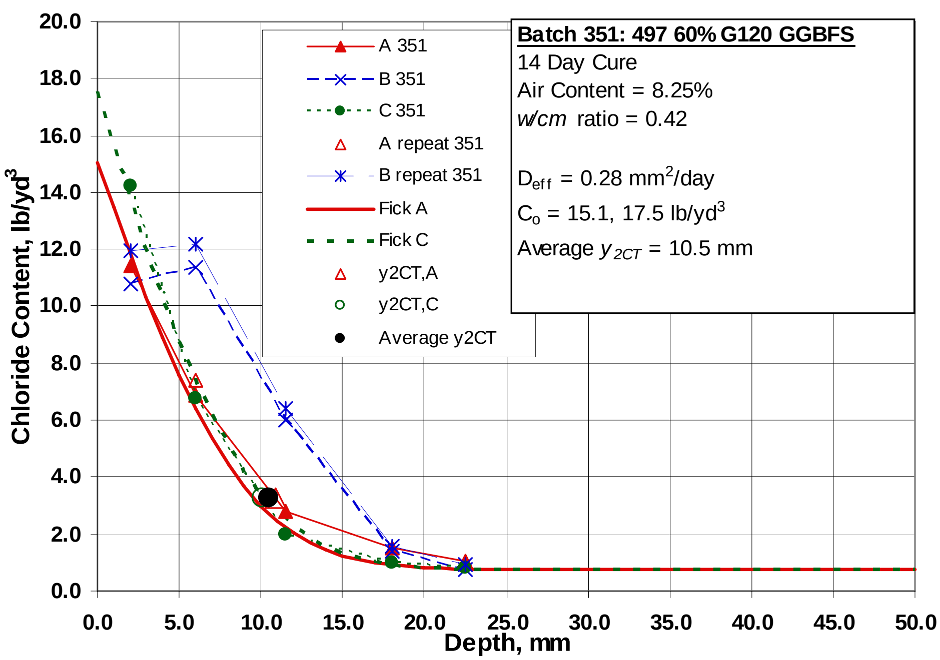


Fig. B.30 Permeability - individual chloride profiles and y_{2CT} for Batch 351 with 21.6% paste, 497 CF, 60% G120, 0.42 *w/cm*, 14-day cure.

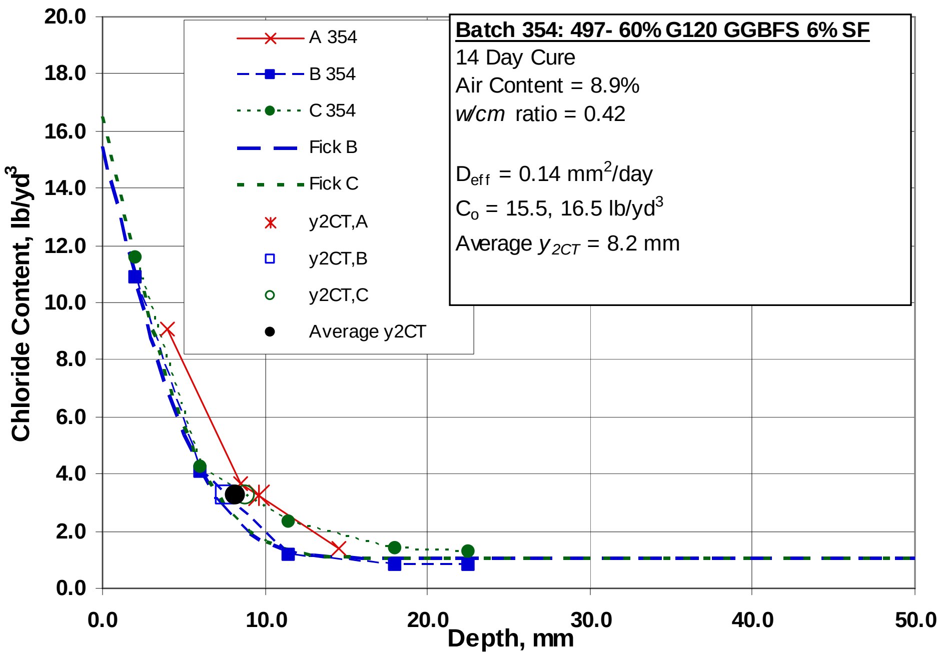


Fig. B.31 Permeability - individual chloride profiles and y_{2CT} for Batch 354 with 21.6% paste, 497 CF, 60% G120 GGBFS 6% SF, 0.42 *w/cm*, 14-day cure.

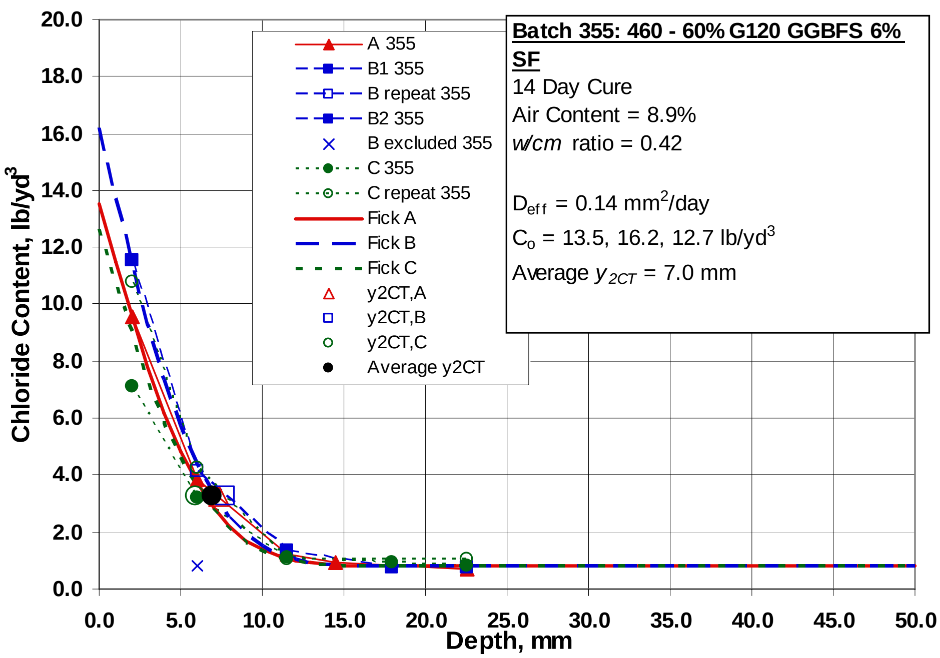


Fig. B.32 Permeability - individual chloride profiles and y_{2CT} for Batch 355 with 20.5% paste, 460 CF, 60% G120 GGBFS 6% SF, 0.42 *w/cm*, 14-day cure.

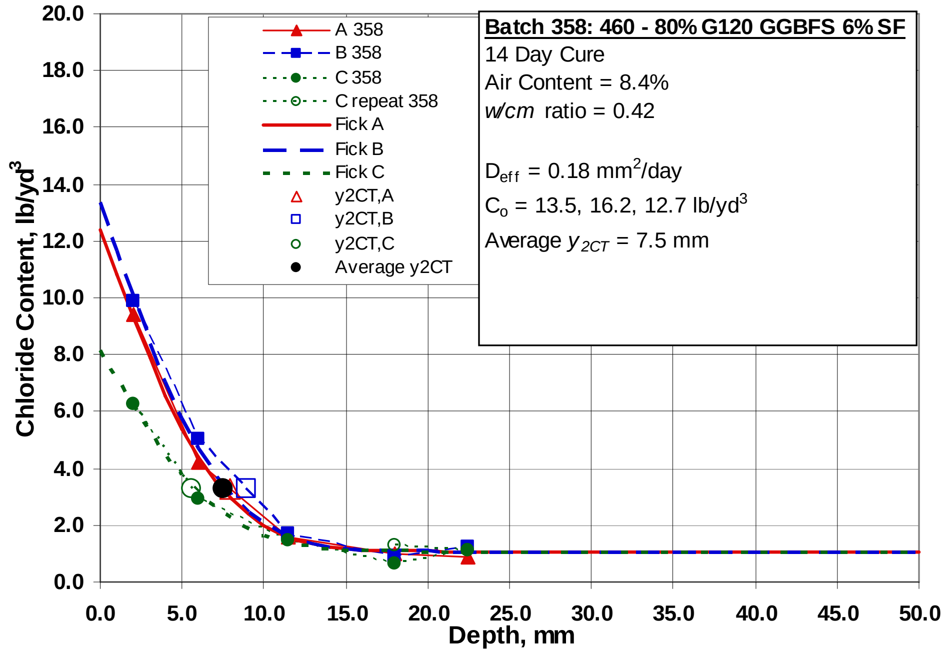


Fig. B.33 Permeability - individual chloride profiles and y_{2CT} for Batch 358 with 20.5% paste, 460 CF, 80% G120 GGBFS 6% SF, 0.42 *w/cm*, 14-day cure.

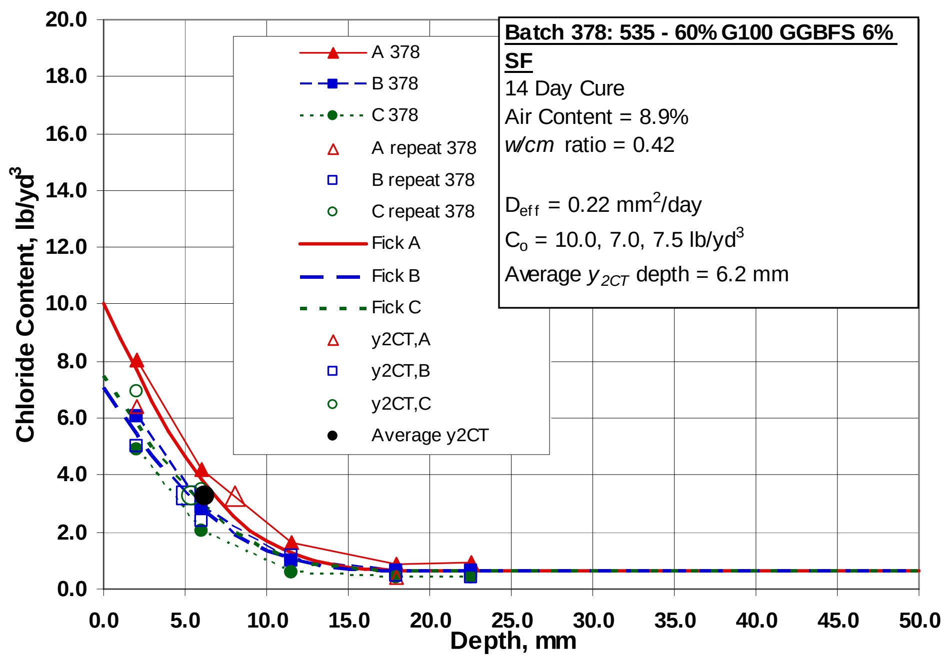


Fig. B.34 Permeability - individual chloride profiles and y_{2CT} for Batch 378 with 23.3% paste, 535 CF, 60% G100 GGBFS 6% SF, 0.42 *w/cm*, 14-day cure.

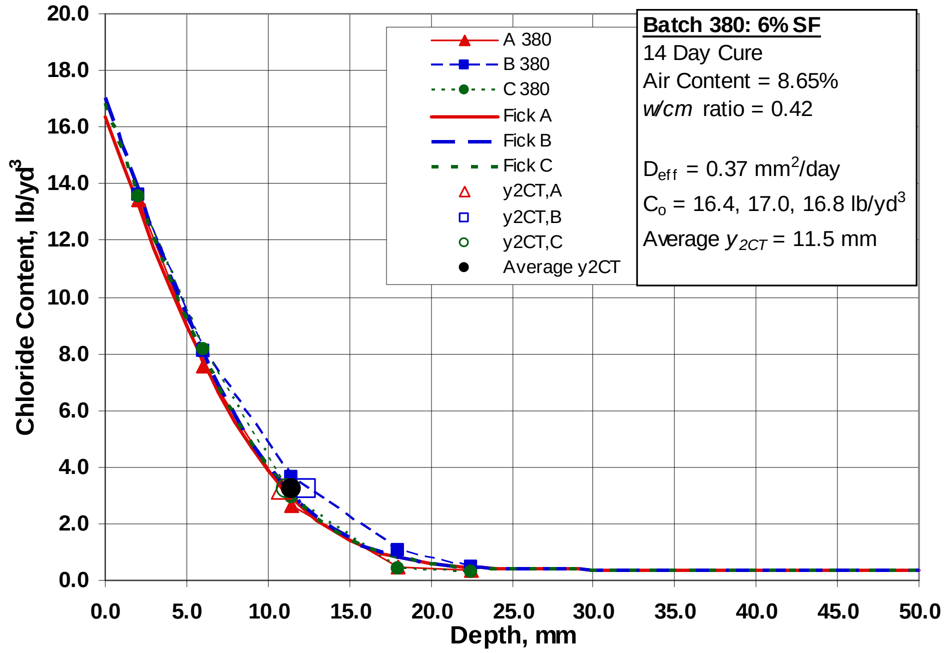


Fig. B.35 Permeability - individual chloride profiles and y_{2CT} for Batch 380 with 23.3% paste, 535 CF, 6% SF, 0.42 *w/cm*, 14-day cure.

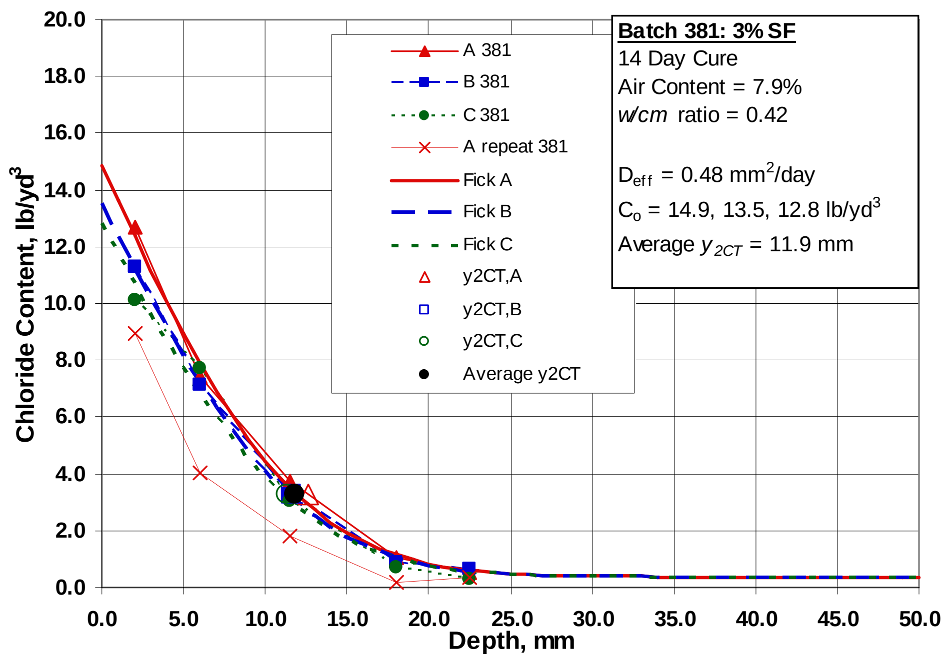


Fig. B.36 Permeability - individual chloride profiles and y_{2CT} for Batch 381 with 23.2% paste, 535 CF, 3% SF, 0.42 *w/cm*, 14-day cure.

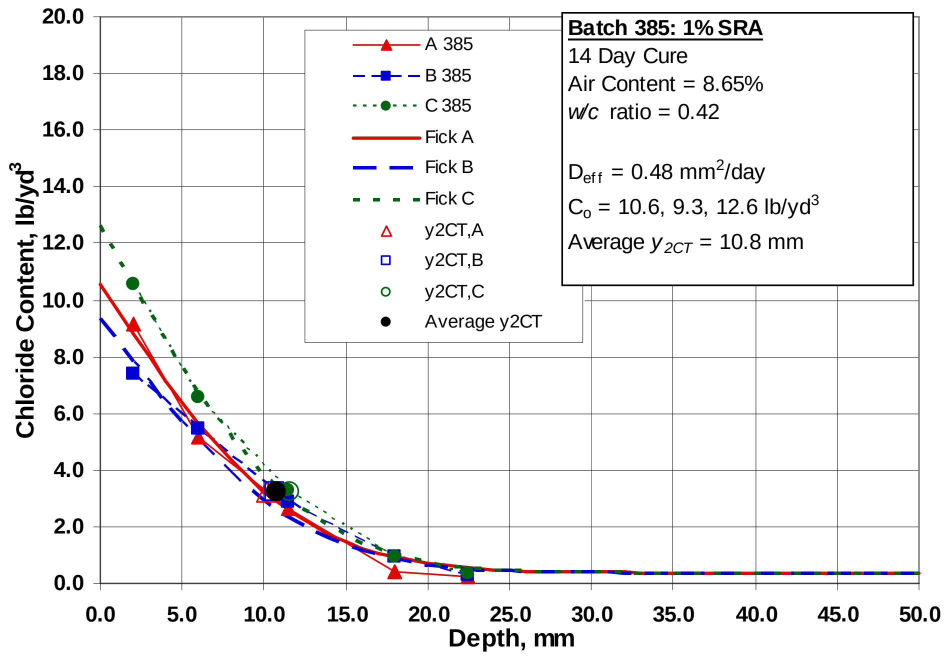


Fig. B.37 Permeability - individual chloride profiles and y_{2CT} for Batch 385 with 23.3% paste, 535 CF, 100% Type I/II cement, 0.42 *w/c*, 14-day cure, 1% SRA.

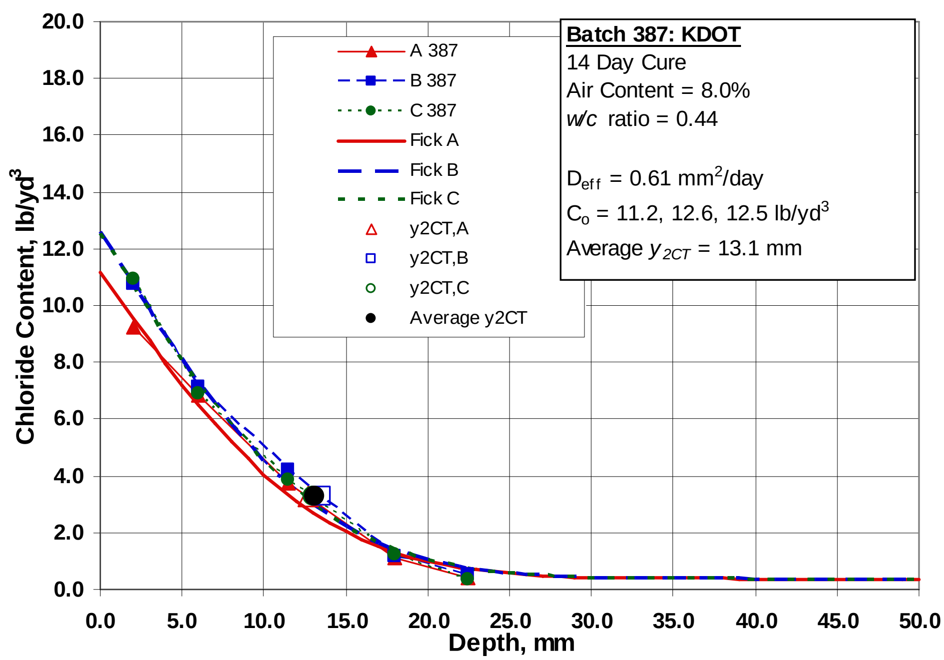


Fig. B.38 Permeability - individual chloride profiles and y_{2CT} for Batch 387 with 26.9% paste, 602 CF, 100% Type I/II cement, 0.44 *w/c*, 14-day cure, KDOT bridge subdeck mix.

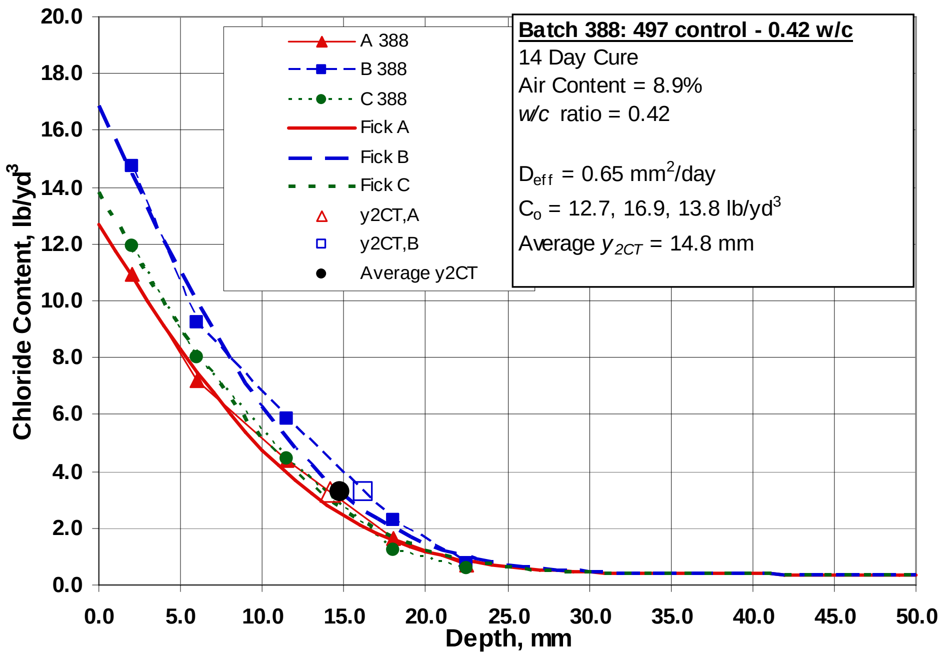


Fig. B.39 Permeability - individual chloride profiles and y_{2CT} for Batch 388 with 21.6% paste, 497 CF, 100% Type I/II cement, 0.42 *w/c*, 14-day cure.

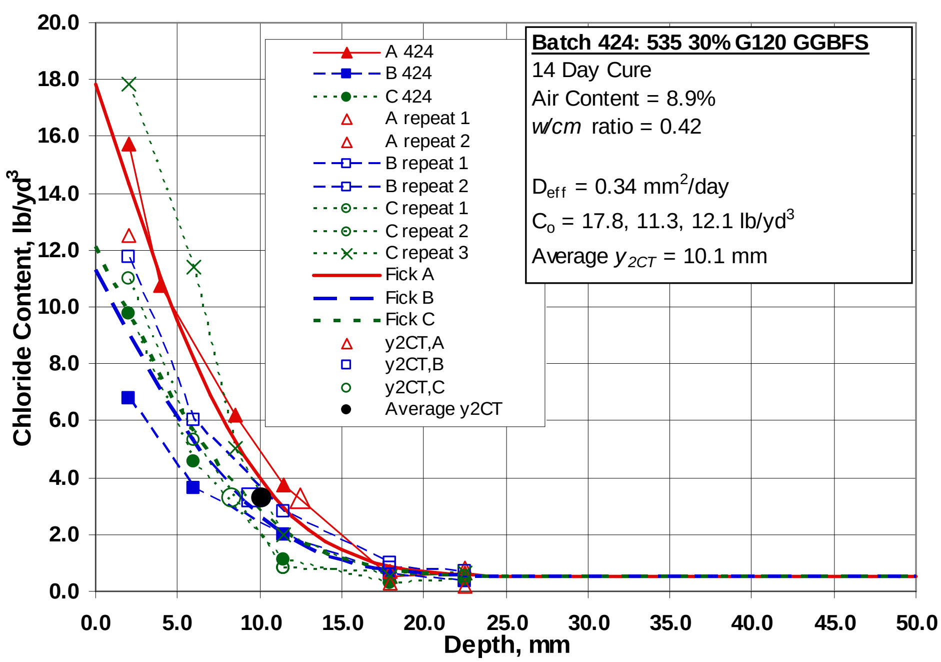


Fig. B.40 Permeability - individual chloride profiles and y_{2CT} for Batch 424 with 23.3% paste, 535 CF, 30% G120 GGBFS, 0.42 *w/cm*, 14-day cure.

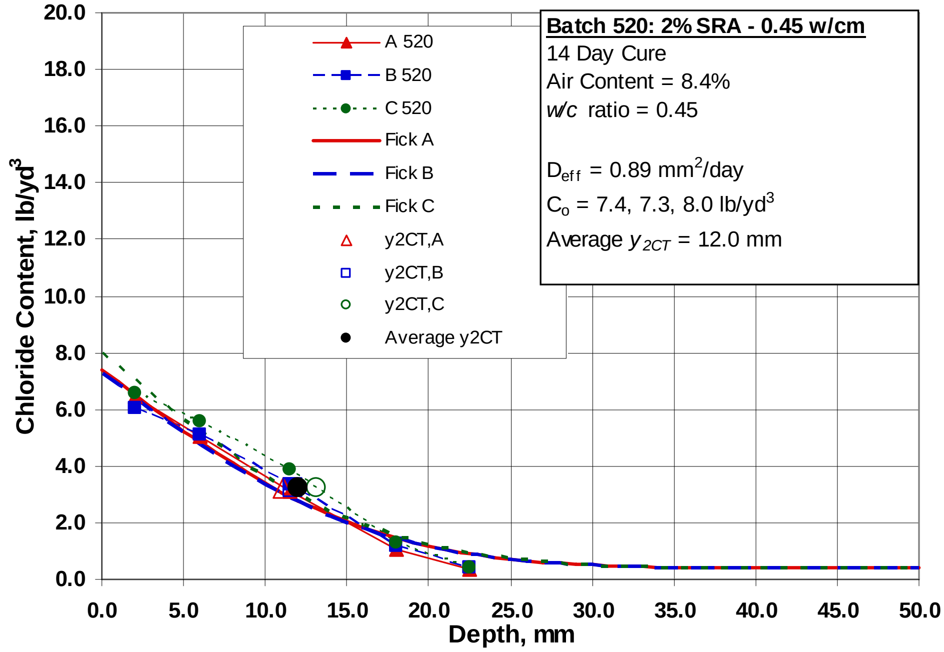


Fig. B.41 Permeability - individual chloride profiles and y_{2CT} for Batch 520 with 24.4% paste, 535 CF, 100% Type I/II cement, 0.45 *w/c*, 14-day cure, 2% SRA.

APPENDIX C

SPECIFICATIONS

C.1 GENERAL

Appendix C contains the most recent Special Provisions to the Kansas DOT Standard Specifications for the construction of Low-Cracking High-Performance Concrete (LC-HPC) bridge decks and references for standard Kansas Department of Transportation Specifications that apply for LC-HPC bridge deck construction. Special provisions exist for aggregate, concrete and construction. Six versions of the aggregate and special provisions, and seven versions of the concrete and construction special provision.

The Standard KDOT Specifications related to bridge deck construction are found online at http://www.ksdot.org/burconsmain/specprov/specifications.asp, including the Special Provisions for Silica Fume Overlays (90M/P-0158).

C.2 AGGREGATE

The six versions of the aggregate special provisions for Phase 1 construction and the Phase 2 special provisions follow, including: 90M-7182, 90M-7326/K7891 Addendum, 90M-7339, 90P-5085, 90M-7359, LCHPC-2, and 07-PS0165.

KANSAS DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION TO THE
STANDARD SPECIFICATIONS, 1990 EDITION

NOTE: This special provision is generally written in the imperative mood. The subject, "the *Contractor*" is implied. Also implied in this language are "*shall*", "*shall be*", or similar words and phrases. The word "*will*" generally pertains to decisions or actions` of the Kansas Department of Transportation.

Section 1102. Delete the entire Section and replace with this:

SECTION 1102

LOW CRACKING HIGH PERFORMANCE - AGGREGATES FOR CONCRETE

1102.1 DESCRIPTION.

This specification is for coarse aggregates, fine aggregates, and mixed aggregates (both coarse and fine material) for use in bridge deck construction.

1102.2 REQUIREMENTS.

a. Coarse Aggregate for Concrete.

(1) Composition. Provide coarse aggregate that is crushed or uncrushed gravel, chat, or crushed stone. (Consider calcite cemented sandstone, rhyolite, basalt and granite as crushed stone).

(2) Quality. The quality requirements for coarse aggregate for bridge decks are in **TABLE 1102-1**:

TABLE 1102-1 Quality Requirements for Coarse Aggregates for Bridge Decks

Concrete Classification	Soundness (min.)	Wear (max.)	Absorption (max.)	Acid Insol. (min.)
Grade 3.5 (AE) (LC-HPC) [1] (Grade 24 (AE) (LC-HPC)) [1]	0.90	40	0.7	55

[1] Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) – Bridge Deck concrete with select coarse aggregate for wear and acid insolubility.

(3) Product Control.

(a) Deleterious Substances. Maximum allowed deleterious substances by weight are:

- Material passing the No. 200 (75 µm) sieve (KT-2) ……………..…… 2.5%
- Shale or Shale-like material (KT-8)……………………..0.5%
- Clay lumps and friable particles (KT-7)…….…….……..1.0%
- Sticks (wet) (KT-35)……………………………..………0.1%

- Coal (AASHTO T 113)……………………….……………0.5%

(b) Uniformity of Supply. Designate or determine the fineness modulus (grading factor) according to the procedure listed in the Construction Manual Part V, Section 17 before delivery, or from the first 10 samples tested and accepted. Provide aggregate that is within ±0.20 of the average fineness modulus.

(4) Do not combine siliceous fine aggregate with siliceous coarse aggregate if neither meet the requirements of **subsection 1102.2c.(2)(a)**. Consider such fine material, regardless of proportioning, as a Basic Aggregate that must conform to the requirements in **subsection 1102.2c.**

(5) Handling Coarse Aggregates.

(a) Segregation. Before acceptance testing, remix all aggregate segregated by transportation or stockpiling operations.

(b) Stockpiling.

- Stockpile accepted aggregates in layers 3 to 5 feet (1.0 to 1.5 m) thick. Berm each layer so that aggregates do not "cone" down into lower layers.
- Keep aggregates from different sources, with different gradings, or with a significantly different specific gravity separated.
- Transport aggregate in a manner that insures uniform gradation.
- Do not use aggregates that have become mixed with earth or foreign material.
- Stockpile or bin all washed aggregate produced or handled by hydraulic methods for 12 hours (minimum) before batching. Rail shipment exceeding 12 hours is acceptable for binning provided the car bodies permit free drainage.
- Provide additional stockpiling or binning in cases of high or non-uniform moisture.

b. Fine Aggregates for Basic Aggregate in MA for Concrete.

(1) Composition.

(a) Type FA-A. Provide either singly or in combination natural occurring sand resulting from the disintegration of siliceous or calcareous rock, or manufactured sand produced by crushing predominately siliceous materials.

(b) Type FA-B. Provide fine granular particles resulting from the crushing of zinc and lead ores (Chat).

(2) Quality.

(a) Mortar strength and Organic Impurities. If the District Materials Engineer determines it is necessary, because of unknown characteristics of new sources or changes in existing sources, provide fine aggregates that comply with these requirements:

- Mortar Strength (Mortar Strength Test, KTMR-26). Compressive strength when combined with Type III (high early strength) cement:
  - At age 24 hours, minimum…………..100%*
  - At age 72 hours, minimum…………..100%*

  *Compared to strengths of specimens of the same proportions, consistency, cement and standard 20-30 Ottawa sand.
- Organic Impurities (Organic Impurities in Fine Aggregate for Concrete Test, AASHTO T 21). The color of the supernatant liquid is equal to or lighter than the reference standard solution.

(b) Hardening characteristics. Specimens made of a mixture of 3 parts FA-B and 1 part cement with sufficient water for molding will harden within 24 hours. There is no hardening requirement for FA-A.

(3) Product Control.

(a) Deleterious Substances.

- Type FA-A: Maximum allowed deleterious substances by weight are:
  - Material passing the No. 200 (75 μm) sieve (KT-2) …………2.0%
  - Shale or Shale-like material (KT-8) …………………………0.5%
  - Clay lumps and friable particles (KT-7)……….. …………… 1.0%
  - Sticks (wet) (KT-35)………………………...………… .. 0.1%
- Type FA-B: Provide materials that are free of organic impurities, sulfates, carbonates, or alkali. Maximum allowed deleterious substances by weight are:
  - Material passing the No. 200 (75 μm) sieve (KT-2)………. .. 2.0%
  - Clay lumps & friable particles (KT-7)…………………….. … 0.25%

(c) Uniformity of Supply. Designate or determine the fineness modulus (grading factor) according to the procedure listed in the Construction Manual Part V, Section 17 before delivery, or from the first 10 samples tested and accepted. Provide aggregate that is within ±0.20 of the average fineness modulus.

(4) Proportioning of Coarse and Fine Aggregate. Use a proven optimization method such as the Shilstone Method.

Do not combine siliceous fine aggregate with siliceous coarse aggregate if neither meet the requirements of **subsection 1102.2c.(2)(a).** Consider such fine material, regardless of proportioning, as a Basic Aggregate and must conform to the requirements in **subsection 1102.2c.**

(5) Handling and Stockpiling Fine Aggregates.

- Keep aggregates from different sources, with different gradings or with a significantly different specific gravity separated.
- Transport aggregate in a manner that insures uniform grading.
- Do not use aggregates that have become mixed with earth or foreign material.
- Stockpile or bin all washed aggregate produced or handled by hydraulic methods for 12 hours (minimum) before batching. Rail shipment exceeding 12 hours is acceptable for binning provided the car bodies permit free drainage.
- Provide additional stockpiling or binning in cases of high or non-uniform moisture.

c. Mixed Aggregates for Concrete.

(1) Composition.

(a) Total Mixed Aggregate (TMA). A natural occurring, predominately siliceous aggregate from a single source that meets the Wetting & Drying Test and grading requirements.

(b) Mixed Aggregate. A combination of basic and coarse aggregates that meet the gradation requirements of Table 1102-3.

- Basic Aggregate (BA). Singly or in combination, a natural occurring, predominately siliceous aggregate that does not meet the grading requirements of Total Mixed Aggregate.

(c) Coarse Aggregate. Granite, crushed sandstone, chat, and gravel. Gravel that is not approved under 1102.2c.(2) may be used, but only with basic aggregate that meets the wetting and drying requirements of TMA.

(2) Quality.

(a) Total Mixed Aggregate.

- Soundness, minimum (KTMR-21) ……..…………0.90
- Wear, maximum (KTMR-25) ……………….….. 50%
- Wetting and Drying Test for Total Mixed Aggregate (KTMR-29)

  Concrete Modulus of Rupture:
  - At 60 days, minimum………………………….550 psi
  - At 365 days, minimum…..…………………..….550 psi

  Expansion:
  - At 180 days, maximum………….…………….0.050%
  - At 365 days, maximum……………………..….0.070%

Aggregates produced from the following general areas are exempt from the Wetting and Drying Test:

- Blue River Drainage Area.
- The Arkansas River from Sterling, west to the Colorado state line.
- The Neosho River from Emporia to the Oklahoma state line.

(b) Basic Aggregate.

- Retain 10% or more of the BA on the No. 8 (2.36 mm) sieve before adding the Coarse Aggregate. Aggregate with less than 10% retained on the No. 8 (2.36 mm) sieve is to be considered a Fine Aggregate described in S**ubsection 1103**. Provide material with less than 5% calcareous material retained on the ⅜" (9.5 mm) sieve.
- Soundness, minimum (KTMR-21)……………….0.90
- Wear, maximum (KTMR-25)……………….….. 50%
- Mortar strength and Organic Impurities. If the District Materials Engineer determines it is necessary, because of unknown characteristics of new sources or changes in existing sources, provide mixed aggregates that comply with these requirements:
    - Mortar Strength (Mortar Strength Test, KTMR-26). Compressive strength when combined with Type III (high early strength) cement:
        - At age 24 hours, minimum…………..100%*
        - At age 72 hours, minimum…………..100%*

          *Compared to strengths of specimens of the same proportions, consistency, cement and standard 20-30 Ottawa sand.
    - Organic Impurities (Organic Impurities in Fine Aggregate for Concrete Test, AASHTO T 21). The color of the supernatant liquid is equal to or lighter than the reference standard solution.

(3) Product Control.

(a) Size Requirement. Provide mixed aggregates that comply with the grading requirements in **TABLE 1102-3**.

TABLE 1102-3 Grading Requirements for Mixed Aggregates for Concrete Bridge Decks

Type	Usage	Percent Retained - Square Mesh Sieves										
		1½ " (37.5 mm)	1" (25.0 mm)	3/4" (19.0 mm)	1/2" (12.5 mm)	3/8" (9.5 mm)	No. 4 (4.75 mm)	No. 8 (2.36 mm)	No. 16 (1.18 mm)	No. 30 (600 µm)	No. 50 (300 µm)	No. 100 150 µm)
MA-4	Optimized for LC-HPC Bridge Decks*	0	2-6	Note[1]	Note[2]	Note[2]	Note[2]	Note[2]	Note[2]	Note[3]	Note[4]	95-100

*Use a proven optimization method, such as the Shilstone Method.
[1]Retain a maximum of 22 percent and a minimum of 5 percent of the material on each individual sieve.
[2]Retain a maximum of 22 percent and a minimum of 8 percent of the material on each individual sieve.
[3]Retain a maximum of 15 percent and a minimum of 8 percent of the material on each individual sieve.
[4]Retain a maximum of 15 percent and a minimum of 5 percent of the material on each individual sieve.

(b) Deleterious Substances. Maximum allowed deleterious substances by weight are:

- Material passing the No. 200 (75 µm)sieve (KT-2)……….. 2.5%
- Shale or Shale-like material (KT-8)…………………..……. 0.5%
- Clay lumps and friable particles (KT-7)………… …… 1.0%
- Sticks (wet) (KT-35)………………………..…………… 0.1%
- Coal (AASHTO T 113)…..……………………..………. 0.5%

(c) Uniformity of Supply. Designate or determine the fineness modulus (grading factor) according to the procedure listed in the Construction Manual Part V, Section 17 before delivery, or from the first 10 samples tested and accepted. Provide aggregate that is within ±0.20 of the average fineness modulus.

(4) Handling Mixed Aggregates.

(a) Segregation. Before acceptance testing, remix all aggregate segregated by transit or stockpiling.

(b) Stockpiling.

- Keep aggregates from different sources, with different gradings or with a significantly different specific gravity separated.
- Transport aggregate in a manner that insures uniform grading.
- Do not use aggregates that have become mixed with earth or foreign material.
- Stockpile or bin all washed aggregate produced or handled by hydraulic methods for 12 hours (minimum) before batching. Rail shipment exceeding 12 hours is acceptable for binning provided the car bodies permit free drainage.
- Provide additional stockpiling or binning in cases of high or non-uniform moisture.

1102.3 TEST METHODS.

Test aggregates according to the applicable provisions of **Subsection 1117.**

1102.4 PREQUALIFICATION.

Aggregates for concrete must be prequalified according to the requirements of **subsection 1101.02**.

1102.5 BASIS OF ACCEPTANCE.

The Engineer will accept aggregates for concrete base on the prequalification required by this specification, and the requirements of **subsection 1101.03**.

08-16-04 M&R (RAM & REK)
7182

KANSAS DEPARTMENT OF TRANSPORTATION

SPECIAL PROVISION TO THE

STANDARD SPECIFICATIONS, 1990 EDITION

NOTE: This special provision is generally written in the imperative mood. The subject, "the *Contractor*" is implied. Also implied in this language are "*shall*", "*shall be*", or similar words and phrases. The word "*will*" generally pertains to decisions or actions` of the Kansas Department of Transportation.

Section 1102. Delete the entire Section and replace with this:

SECTION 1102

LOW CRACKING HIGH PERFORMANCE - AGGREGATES FOR CONCRETE

1102.1 DESCRIPTION.

This specification is for coarse aggregates, fine aggregates, and mixed aggregates (both coarse and fine material) for use in bridge deck construction.

1102.2 REQUIREMENTS.

a. Coarse Aggregate for Concrete.

(1) Composition. Provide coarse aggregate that is crushed or uncrushed gravel, chat, or crushed stone. (Consider calcite cemented sandstone, rhyolite, basalt and granite as crushed stone).

(2) Quality. The quality requirements for coarse aggregate for bridge decks are in **TABLE 1102-1**:

TABLE 1102-1 Quality Requirements for Coarse Aggregates for Bridge Decks

Concrete Classification	Soundness (min.)	Wear (max.)	Absorption (max.)	Acid Insol. (min.)
Grade 3.5 (AE) (LC-HPC) [1] (Grade 24 (AE) (LC-HPC)) [1]	0.90	40	0.7	55

[1] Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) – Bridge Deck concrete with select coarse aggregate for wear and acid insolubility.

(3) Product Control.

(a) Deleterious Substances. Maximum allowed deleterious substances by weight are:

- Material passing the No. 200 (75 µm) sieve (KT-2) ………….…… 2.5%
- Shale or Shale-like material (KT-8)……………………………….. 0.5%

- Clay lumps and friable particles (KT-7)…………………..1.0%
- Sticks (wet) (KT-35) ………………..…………… 0.1%
- Coal (AASHTO T 113) ……….…….……… 0.5%

(b) Uniformity of Supply. Designate or determine the fineness modulus (grading factor) according to the procedure listed in the Construction Manual Part V, Section 17 before delivery, or from the first 10 samples tested and accepted. Provide aggregate that is within ±0.20 of the average fineness modulus.

(4) Do not combine siliceous fine aggregate with siliceous coarse aggregate if neither meet the requirements of **subsection 1102.2c.(2)(a)**. Consider such fine material, regardless of proportioning, as a Basic Aggregate that must conform to the requirements in **subsection 1102.2c.**

(5) Handling Coarse Aggregates.

(a) Segregation. Before acceptance testing, remix all aggregate segregated by transportation or stockpiling operations.

(b) Stockpiling.

- Stockpile accepted aggregates in layers 3 to 5 feet (1.0 to 1.5 m) thick. Berm each layer so that aggregates do not "cone" down into lower layers.
- Keep aggregates from different sources, with different gradings, or with a significantly different specific gravity separated.
- Transport aggregate in a manner that insures uniform gradation.
- Do not use aggregates that have become mixed with earth or foreign material.
- Stockpile or bin all washed aggregate produced or handled by hydraulic methods for 12 hours (minimum) before batching. Rail shipment exceeding 12 hours is acceptable for binning provided the car bodies permit free drainage.
- Provide additional stockpiling or binning in cases of high or non-uniform moisture.

b. Fine Aggregates for Basic Aggregate in MA for Concrete.

(1) Composition.

(a) Type FA-A. Provide either singly or in combination natural occurring sand resulting from the disintegration of siliceous or calcareous rock, or manufactured sand produced by crushing predominately siliceous materials.

(b) Type FA-B. Provide fine granular particles resulting from the crushing of zinc and lead ores (Chat).

(2) Quality.

(a) Mortar strength and Organic Impurities. If the District Materials Engineer determines it is necessary, because of unknown characteristics of new sources or changes in existing sources, provide fine aggregates that comply with these requirements:

- Mortar Strength (Mortar Strength Test, KTMR-26). Compressive strength when combined with Type III (high early strength) cement:
  - At age 24 hours, minimum…………..100%*
  - At age 72 hours, minimum…………..100%*

  *Compared to strengths of specimens of the same proportions, consistency, cement and standard 20-30 Ottawa sand.
- Organic Impurities (Organic Impurities in Fine Aggregate for Concrete Test, AASHTO T 21). The color of the supernatant liquid is equal to or lighter than the reference standard solution.

(b) Hardening characteristics. Specimens made of a mixture of 3 parts FA-B and 1 part cement with sufficient water for molding will harden within 24 hours. There is no hardening requirement for FA-A.

(3) Product Control.

(a) Deleterious Substances.

- Type FA-A: Maximum allowed deleterious substances by weight are:
  - Material passing the No. 200 (75 μm) sieve (KT-2)…2.0%
  - Shale or Shale-like material (KT-8) …………………0.5%
  - Clay lumps and friable particles (KT-7)……..……… 1.0%
  - Sticks (wet) (KT-35)…………………...…………... 0.1%
- Type FA-B: Provide materials that are free of organic impurities, sulfates, carbonates, or alkali. Maximum allowed deleterious substances by weight are:
  - Material passing the No. 200 (75 μm) sieve (KT-2) .. 2.0%
  - Clay lumps & friable particles (KT-7)………….. … 0.25%

(c) Uniformity of Supply. Designate or determine the fineness modulus (grading factor) according to the procedure listed in the Construction Manual Part V, Section 17 before delivery, or from the first 10 samples tested and accepted. Provide aggregate that is within ±0.20 of the average fineness modulus.

(4) Proportioning of Coarse and Fine Aggregate. Use a proven optimization method such as the Shilstone Method or the KU Mix Method.

Do not combine siliceous fine aggregate with siliceous coarse aggregate if neither meet the requirements of **subsection 1102.2c.(2)(a).** Consider such fine material, regardless of proportioning, as a Basic Aggregate and must conform to the requirements in **subsection 1102.2c.**

(5) Handling and Stockpiling Fine Aggregates.

- Keep aggregates from different sources, with different gradings or with a significantly different specific gravity separated.
- Transport aggregate in a manner that insures uniform grading.
- Do not use aggregates that have become mixed with earth or foreign material.
- Stockpile or bin all washed aggregate produced or handled by hydraulic methods for 12 hours (minimum) before batching. Rail shipment exceeding 12 hours is acceptable for binning provided the car bodies permit free drainage.
- Provide additional stockpiling or binning in cases of high or non-uniform moisture.

c. Mixed Aggregates for Concrete.

(1) Composition.

(a) Total Mixed Aggregate (TMA). A natural occurring, predominately siliceous aggregate from a single source that meets the Wetting & Drying Test (KTMR-23) and grading requirements.

(b) Mixed Aggregate. A combination of basic and coarse aggregates that meet the gradation requirements of Table 1102-3.

- Basic Aggregate (BA). Singly or in combination, a natural occurring, predominately siliceous aggregate that does not meet the grading requirements of Total Mixed Aggregate.

(c) Coarse Aggregate. Granite, crushed sandstone, chat, and gravel. Gravel that is not approved under 1102.2c.(2) may be used, but only with basic aggregate that meets the wetting and drying requirements of TMA.

(2) Quality.

(a) Total Mixed Aggregate.

- Soundness, minimum (KTMR-21) ……..…………0.90
- Wear, maximum (KTMR-25) ……………….….. 50%
- Wetting and Drying Test (KTMR-23) for Total Mixed Aggregate

  Concrete Modulus of Rupture:
  - At 60 days, minimum………………………….550 psi
  - At 365 days, minimum…..……………….……550 psi

  Expansion:
  - At 180 days, maximum………….…………….0.050%
  - At 365 days, maximum……………….…….…0.070%

Aggregates produced from the following general areas are exempt from the Wetting and Drying Test:

- Blue River Drainage Area.
- The Arkansas River from Sterling, west to the Colorado state line.
- The Neosho River from Emporia to the Oklahoma state line.

(b) Basic Aggregate.

- Retain 10% or more of the BA on the No. 8 (2.36 mm) sieve before adding the Coarse Aggregate. Aggregate with less than 10% retained on the No. 8 (2.36 mm) sieve is to be considered a Fine Aggregate described in S**ubsection 1103**. Provide material with less than 5% calcareous material retained on the ⅜" (9.5 mm) sieve.
- Soundness, minimum (KTMR-21)……………….0.90
- Wear, maximum (KTMR-25)………………….. 50%
- Mortar strength and Organic Impurities. If the District Materials Engineer determines it is necessary, because of unknown characteristics of new sources or changes in existing sources, provide mixed aggregates that comply with these requirements:
  - Mortar Strength (Mortar Strength Test, KTMR-26). Compressive strength when combined with Type III (high early strength) cement:
    - At age 24 hours, minimum…………..100%*
    - At age 72 hours, minimum…………..100%*

      *Compared to strengths of specimens of the same proportions, consistency, cement and standard 20-30 Ottawa sand.
  - Organic Impurities (Organic Impurities in Fine Aggregate for Concrete Test, AASHTO T 21). The color of the supernatant liquid is equal to or lighter than the reference standard solution.

(3) Product Control.

(a) Size Requirement. Provide mixed aggregates that comply with the grading requirements in **TABLE 1102-3**.

TABLE 1102-3 Grading Requirements for Mixed Aggregates for Concrete Bridge Decks

Type	Usage	Percent Retained - Square Mesh Sieves										
		1½ " (37.5 mm)	1" (25.0 mm)	3/4" (19.0 mm)	1/2" (12.5 mm)	3/8" (9.5 mm)	No. 4 (4.75 mm)	No. 8 (2.36 mm)	No. 16 (1.18 mm)	No. 30 (600 µm)	No. 50 (300 µm)	No. 100 150 µm)
MA-4	Optimized for LC-HPC Bridge Decks*	0	2-6	Note[1]	Note[2]	Note[2]	Note[2]	Note[2]	Note[2]	Note[3]	Note[4]	95-100

*Use a proven optimization method, such as the Shilstone Method or the KU Mix Method.
[1]Retain a maximum of 18 percent and a minimum of 5 percent of the material on each individual sieve.
[2]Retain a maximum of 18 percent and a minimum of 8 percent of the material on each individual sieve.
[3]Retain a maximum of 15 percent and a minimum of 8 percent of the material on each individual sieve.
[4]Retain a maximum of 15 percent and a minimum of 5 percent of the material on each individual sieve.

(b) Deleterious Substances. Maximum allowed deleterious substances by weight are:

- Material passing the No. 200 (75 µm)sieve (KT-2)……….. 2.5%
- Shale or Shale-like material (KT-8)…………………..……. 0.5%
- Clay lumps and friable particles (KT-7)……………… 1.0%
- Sticks (wet) (KT-35)………………………..…………… 0.1%
- Coal (AASHTO T 113)…..……………………..………. 0.5%

(c) Uniformity of Supply. Designate or determine the fineness modulus (grading factor) according to the procedure listed in the Construction Manual Part V, Section 17 before delivery, or from the first 10 samples tested and accepted. Provide aggregate that is within ±0.20 of the average fineness modulus.

(4) Handling Mixed Aggregates.

(a) Segregation. Before acceptance testing, remix all aggregate segregated by transit or stockpiling.

(b) Stockpiling.

- Keep aggregates from different sources, with different gradings or with a significantly different specific gravity separated.
- Transport aggregate in a manner that insures uniform grading.
- Do not use aggregates that have become mixed with earth or foreign material.
- Stockpile or bin all washed aggregate produced or handled by hydraulic methods for 12 hours (minimum) before batching. Rail shipment exceeding 12 hours is acceptable for binning provided the car bodies permit free drainage.
- Provide additional stockpiling or binning in cases of high or non-uniform moisture.

1102.3 TEST METHODS.

Test aggregates according to the applicable provisions of **Section 1117.**

1102.4 PREQUALIFICATION.

Aggregates for concrete must be prequalified according to the requirements of **subsection 1101.02**.

1102.5 BASIS OF ACCEPTANCE.

The Engineer will accept aggregates for concrete base on the prequalification required by this specification, and the requirements of **subsection 1101.03**.

06-15-06 M&R (RAM & REK)
7326

Promptly sign and date on the line below, then **FAX IT TO the Estimating Section at (785) 368-6240, EVEN IF NOT BIDDING**. Any instructions not followed will result in your bid being declared irregular. If these changes affect any of your subcontractors or suppliers, **IT IS YOUR RESPONSIBILITY** to inform them. These changes are part of the contract for this project(s). Please contact me at (785) 296-3576, if there are questions. Thank you for your cooperation.

Kansas Department of Transportation

Bureau of Construction and Maintenance
Estimating Section

To: Contract Bidders

From: Albert Oyerly, P.E. - Estimating Engineer

Date: July 12, 2006

Contract No.: 506072514

Subject: Project Notice for the **July 19, 2006 Letting**

69-54 K 7891-01 LINN COUNTY- GRADING, SURFACING, & BRIDGES

For Contractor's Information:

1. Pumping of LC-HPC will be allowed if the contractor can show proficiency at the placing of the qualification slab.
2. Grooving of the finished surface may be done with equipment that is not self propelled providing contractor can show proficiency with the equipment.
3. The bridge rail should be cast using LC-HPC concrete using the following adjusted gradation to allow for the limited cover steel cover in the corral rail. Note no 1" aggregate should be used.

TABLE 1102-3 Grading Requirements for Mixed Aggregates for Concrete Bridge Decks

Type	Usage	Percent Retained - Square Mesh Sieves										
		1½" (37.5 mm)	1" (25.0 mm)	3/4" (19.0 mm)	1/2" (12.5 mm)	3/8" (9.5 mm)	No. 4 (4.75 mm)	No. 8 (2.36 mm)	No. 16 (1.18 mm)	No. 30 (600 µm)	No. 50 (300 µm)	No. 100 150 µm)
MA-4	Optimized for LC-HPC Bridge Decks*	0	0	2-6	Note[1]	Note[2]	Note[2]	Note[2]	Note[2]	Note[3]	Note[4]	95-100

*Use a proven optimization method, such as the Shilstone Method or the KU Mix Method.

[1]Retain a maximum of 18 percent and a minimum of 5 percent of the material on each individual sieve.

[2]Retain a maximum of 18 percent and a minimum of 8 percent of the material on each individual sieve.

[3]Retain a maximum of 15 percent and a minimum of 8 percent of the material on each individual sieve.

[4]Retain a maximum of 15 percent and a minimum of 5 percent of the material on each individual sieve.

4. Allowable Construction Loads in 90M-7296 is incorrect.

   As the curing process is 14 days no traffic will be allowed on the deck for 14 days. Legal loads will be allowed on the deck after the curing process is complete (14 days). Heavy Stationary Loads and Greater than Legal load requirements remain the same.

5. The cover to the bottom mat of reinforcing steel in the slab shown on Bridges (053), (057), & (060), has been changed to 35 mm since the LC-HP Concrete has a 1" maximum aggregate size. The plans will be revised to reflect these changes.

Kansas Department of Transportation Bureau of Construction & Maintenance July 12, 2006	July 19, 2006 Letting Project No. 69-54 K 7891-01 Contract No. 506072514 Page 2 of 2

The special provision **90M-7183 (LOW CRACKING HIGH PERFORMANCE CONCRETE - CEMENT)** is not needed on this project and is being removed form the contract. This change is reflected in the modified special provision list that is part of this addendum. This modified special provision list **MUST** be included when submitting a bid.

Line item numbers 90, 152, & 202 (**TRIAL SLAB**) have been changed to (**QUALIFICATION SLAB**).

Our web site (http://www.ksdot.org/hwycont.asp) has all these revisions. Select the "**Letting Information**", locate this project and then choose "**Addendum # 1**". The revised proposal schedule and modified special provision list are part of this selection. You can download the added special provisions from the same web site by selecting the "**Special Provisions**" and "**List All Special Provisions**" buttons.

If you are **NOT** using the **EXPEDITE** bidding system you **MUST** download the proposal schedule sheets from our web site, as described above. Write your vendor number and contractor's name in **INK** at the bottom of each page of the proposal schedule as appears on the original. These pages **MUST** be used when submitting a bid.

You **MUST** have the latest **Adobe Acrobat Reader** to print these sheets. There is a link on our web page that allows you to download the free **Adobe Acrobat Reader**. If you do not have access to Internet, please contact me so I can send you a copy of proposal schedule sheets and modified special provision list.

These changes are also available in an electronic file format if you are using the **EXPEDITE** bidding system, which can be downloaded from the same web site. In order to have these changes reflected on your EXPEDITE file you **MUST** also download its associated "amendment file" which is included with this Internet file. If you would like to start using the EXPEDITE program, the software can be downloaded from our web site. If you need additional support, please contact us.

These plan revisions are incorporated by reference into the proposal and will be further documented with revised plan sheets issued after the letting. The revised proposal schedule and special provision list will be included in the contract prior to signing.

Failure to follow these instructions will be basis for declaring the bid irregular.

___

(Company Name) (Signature) (Date)

C: District 4

90M-7339
Sheet 1 of 6
1102

KANSAS DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION TO THE
STANDARD SPECIFICATIONS, 1990 EDITION

NOTE: This special provision is generally written in the imperative mood. The subject, "the *Contractor*" is implied. Also implied in this language are "*shall*", "*shall be*", or similar words and phrases. The word "*will*" generally pertains to decisions or actions` of the Kansas Department of Transportation.

Section 1102. Delete the entire Section and replace with this:

SECTION 1102

LOW CRACKING HIGH PERFORMANCE - AGGREGATES FOR CONCRETE

1102.1 DESCRIPTION.

This specification is for coarse aggregates, fine aggregates, and mixed aggregates (both coarse and fine material) for use in bridge deck construction.

1102.2 REQUIREMENTS.

a. Coarse Aggregate for Concrete.

(1) Composition. Provide coarse aggregate that is crushed or uncrushed gravel, chat, or crushed stone. (Consider calcite cemented sandstone, rhyolite, basalt and granite as crushed stone).

(2) Quality. The quality requirements for coarse aggregate for bridge decks are in **TABLE 1102-1**:

TABLE 1102-1 Quality Requirements for Coarse Aggregates for Bridge Decks

Concrete Classification	Soundness (min.)	Wear (max.)	Absorption (max.)	Acid Insol. (min.)
Grade 3.5 (AE) (LC-HPC) [1] (Grade 24 (AE) (LC-HPC)) [1]	0.90	40	0.7	55

[1] Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) – Bridge Deck concrete with select coarse aggregate for wear and acid insolubility.

(3) Product Control.

(a) Deleterious Substances. Maximum allowed deleterious substances by weight are:

- Material passing the No. 200 (75 μm) sieve (KT-2)……………..…… 2.5%
- Shale or Shale-like material (KT-8)……………………………….. 0.5%
- Clay lumps and friable particles (KT-7)………..…………………….. 1.0%
- Sticks (wet) (KT-35)……………………………...………………0.1%
- Coal (AASHTO T 113)……………………………..…….…………0.5%

90M-7339
Sheet 2 of 6
1102

(b) Uniformity of Supply. Designate or determine the fineness modulus (grading factor) according to the procedure listed in the Construction Manual Part V, Section 17 before delivery, or from the first 10 samples tested and accepted. Provide aggregate that is within ±0.20 of the average fineness modulus.

(4) Do not combine siliceous fine aggregate with siliceous coarse aggregate if neither meet the requirements of **subsection 1102.2c.(2)(a)**. Consider such fine material, regardless of proportioning, as a Basic Aggregate that must conform to the requirements in **subsection 1102.2c.**

(5) Handling Coarse Aggregates.

(a) Segregation. Before acceptance testing, remix all aggregate segregated by transportation or stockpiling operations.

(b) Stockpiling.

- Stockpile accepted aggregates in layers 3 to 5 feet (1.0 to 1.5 m) thick. Berm each layer so that aggregates do not "cone" down into lower layers.
- Keep aggregates from different sources, with different gradings, or with a significantly different specific gravity separated.
- Transport aggregate in a manner that insures uniform gradation.
- Do not use aggregates that have become mixed with earth or foreign material.
- Stockpile or bin all washed aggregate produced or handled by hydraulic methods for 12 hours (minimum) before batching. Rail shipment exceeding 12 hours is acceptable for binning provided the car bodies permit free drainage.
- Provide additional stockpiling or binning in cases of high or non-uniform moisture.

b. Fine Aggregates for Basic Aggregate in MA for Concrete.

(1) Composition.

(a) Type FA-A. Provide either singly or in combination natural occurring sand resulting from the disintegration of siliceous or calcareous rock, or manufactured sand produced by crushing predominately siliceous materials.

(b) Type FA-B. Provide fine granular particles resulting from the crushing of zinc and lead ores (Chat).

(2) Quality.

(a) Mortar strength and Organic Impurities. If the District Materials Engineer determines it is necessary, because of unknown characteristics of new sources or changes in existing sources, provide fine aggregates that comply with these requirements:

- Mortar Strength (Mortar Strength Test, KTMR-26). Compressive strength when combined with Type III (high early strength) cement:
  - At age 24 hours, minimum…………..100%*
  - At age 72 hours, minimum…………..100%*

*Compared to strengths of specimens of the same proportions, consistency, cement and standard 20-30 Ottawa sand.

- Organic Impurities (Organic Impurities in Fine Aggregate for Concrete Test, AASHTO T 21). The color of the supernatant liquid is equal to or lighter than the reference standard solution.

(b) Hardening characteristics. Specimens made of a mixture of 3 parts FA-B and 1 part cement with sufficient water for molding will harden within 24 hours. There is no hardening requirement for FA-A.

(3) Product Control.

(a) Deleterious Substances.

- Type FA-A: Maximum allowed deleterious substances by weight are:
  - Material passing the No. 200 (75 μm) sieve (KT-2)............2.0%
  - Shale or Shale-like material (KT-8) 0.5%
  - Clay lumps and friable particles (KT-7)........................... 1.0%
  - Sticks (wet) (KT-35).. 0.1%
- Type FA-B: Provide materials that are free of organic impurities, sulfates, carbonates, or alkali. Maximum allowed deleterious substances by weight are:
  - Material passing the No. 200 (75 μm) sieve (KT-2)............ 2.0%
  - Clay lumps & friable particles (KT-7).............................. 0.25%

(c) Uniformity of Supply. Designate or determine the fineness modulus (grading factor) according to the procedure listed in the Construction Manual Part V, Section 17 before delivery, or from the first 10 samples tested and accepted. Provide aggregate that is within ±0.20 of the average fineness modulus.

(4) Proportioning of Coarse and Fine Aggregate. Use a proven optimization method such as the Shilstone Method or the KU Mix Method.

Do not combine siliceous fine aggregate with siliceous coarse aggregate if neither meet the requirements of **subsection 1102.2c.(2)(a).** Consider such fine material, regardless of proportioning, as a Basic Aggregate and must conform to the requirements in **subsection 1102.2c.**

(5) Handling and Stockpiling Fine Aggregates.

- Keep aggregates from different sources, with different gradings or with a significantly different specific gravity separated.
- Transport aggregate in a manner that insures uniform grading.
- Do not use aggregates that have become mixed with earth or foreign material.
- Stockpile or bin all washed aggregate produced or handled by hydraulic methods for 12 hours (minimum) before batching. Rail shipment exceeding 12 hours is acceptable for binning provided the car bodies permit free drainage.
- Provide additional stockpiling or binning in cases of high or non-uniform moisture.

c. Mixed Aggregates for Concrete.

(1) Composition.

(a) Total Mixed Aggregate (TMA). A natural occurring, predominately siliceous aggregate from a single source that meets the Wetting & Drying Test (KTMR-23) and grading requirements.

90M-7339
Sheet 4 of 6
1102

(b) Mixed Aggregate. A combination of basic and coarse aggregates that meet the gradation requirements of Table 1102-3.

- Basic Aggregate (BA). Singly or in combination, a natural occurring, predominately siliceous aggregate that does not meet the grading requirements of Total Mixed Aggregate.

(c) Coarse Aggregate. Granite, crushed sandstone, chat, and gravel. Gravel that is not approved under 1102.2c.(2) may be used, but only with basic aggregate that meets the wetting and drying requirements of TMA.

(2) Quality.

(a) Total Mixed Aggregate.

- Soundness, minimum (KTMR-21) ……..…………0.90
- Wear, maximum (KTMR-25) ………………..….. 50%
- Wetting and Drying Test (KTMR-23) for Total Mixed Aggregate
  Concrete Modulus of Rupture:
  - At 60 days, minimum………………………….550 psi
  - At 365 days, minimum…..…………………..….550 psi

  Expansion:
  - At 180 days, maximum………………..……….0.050%
  - At 365 days, maximum……………………..…….0.070%

  Aggregates produced from the following general areas are exempt from the Wetting and Drying Test:
  - Blue River Drainage Area.
  - The Arkansas River from Sterling, west to the Colorado state line.
  - The Neosho River from Emporia to the Oklahoma state line.

(b) Basic Aggregate.

- Retain 10% or more of the BA on the No. 8 (2.36 mm) sieve before adding the Coarse Aggregate. Aggregate with less than 10% retained on the No. 8 (2.36 mm) sieve is to be considered a Fine Aggregate described in S**ubsection 1103**. Provide material with less than 5% calcareous material retained on the ⅜" (9.5 mm) sieve.
- Soundness, minimum (KTMR-21)……………….0.90
- Wear, maximum (KTMR-25)……………….….. 50%
- Mortar strength and Organic Impurities. If the District Materials Engineer determines it is necessary, because of unknown characteristics of new sources or changes in existing sources, provide mixed aggregates that comply with these requirements:
  - Mortar Strength (Mortar Strength Test, KTMR-26). Compressive strength when combined with Type III (high early strength) cement:
    - At age 24 hours, minimum…………..100%*
    - At age 72 hours, minimum…………..100%*

    *Compared to strengths of specimens of the same proportions, consistency, cement and standard 20-30 Ottawa sand.

- Organic Impurities (Organic Impurities in Fine Aggregate for Concrete Test, AASHTO T 21). The color of the supernatant liquid is equal to or lighter than the reference standard solution.

(3) Product Control.

(a) Size Requirement. Provide mixed aggregates that comply with the grading requirements in **TABLE 1102-3 & 1102-4**.

TABLE 1102-3 Grading Requirements for Mixed Aggregates for Concrete Bridge Decks and Barrier Rail

Type	Usage	Percent Retained - Square Mesh Sieves										
		1½ " (37.5 mm)	1" (25.0 mm)	3/4" (19.0 mm)	1/2" (12.5 mm)	3/8" (9.5 mm)	No. 4 (4.75 mm)	No. 8 (2.36 mm)	No. 16 (1.18 mm)	No. 30 (600 µm)	No. 50 (300 µm)	No. 100 150 µm)
MA-4	Optimized for LC-HPC Bridge Decks*	0	2-6	Note[1]	Note[2]	Note[2]	Note[2]	Note[2]	Note[2]	Note[3]	Note[4]	95-100

*Use a proven optimization method, such as the Shilstone Method or the KU Mix Method.
[1]Retain a maximum of 18 percent and a minimum of 5 percent of the material on each individual sieve.
[2]Retain a maximum of 18 percent and a minimum of 8 percent of the material on each individual sieve.
[3]Retain a maximum of 15 percent and a minimum of 8 percent of the material on each individual sieve.
[4]Retain a maximum of 15 percent and a minimum of 5 percent of the material on each individual sieve.

TABLE 1102-4 Grading Requirements for Mixed Aggregates for Concrete Corral Bridge Rail

Type	Usage	Percent Retained - Square Mesh Sieves										
		1½ " (37.5 mm)	1" (25.0 mm)	3/4" (19.0 mm)	1/2" (12.5 mm)	3/8" (9.5 mm)	No. 4 (4.75 mm)	No. 8 (2.36 mm)	No. 16 (1.18 mm)	No. 30 (600 µm)	No. 50 (300 µm)	No. 100 150 µm)
MA-4	Optimized for LC-HPC Bridge Rail*	0	0	2-6	Note[1]	Note[2]	Note[2]	Note[2]	Note[2]	Note[3]	Note[4]	95-100

*Use a proven optimization method, such as the Shilstone Method or the KU Mix Method.
[1]Retain a maximum of 20 percent and a minimum of 8 percent of the material on each individual sieve.
[2]Retain a maximum of 15 percent and a minimum of 5 percent of the material on each individual sieve.
[3]Retain a maximum of 15 percent and a minimum of 8 percent of the material on each individual sieve.
[4]Retain a maximum of 15 percent and a minimum of 5 percent of the material on each individual sieve.

(b) The adjusted gradation for Corral rail (Table 1102-4) is not necessary for Barrier rail (Table 1102-3).

(c) Deleterious Substances. Maximum allowed deleterious substances by weight are:

- Material passing the No. 200 (75 µm) sieve (KT-2)……….. 2.5%
- Shale or Shale-like material (KT-8)……………………..……. 0.5%
- Clay lumps and friable particles (KT-7)…………………… 1.0%
- Sticks (wet) (KT-35)………………………….…………… 0.1%
- Coal (AASHTO T 113)…..…………………………..………. 0.5%

(d) Uniformity of Supply. Designate or determine the fineness modulus (grading factor) according to the procedure listed in the Construction Manual Part V, Section 17 before delivery, or from the first 10 samples tested and accepted. Provide aggregate that is within ±0.20 of the average fineness modulus.

(4) Handling Mixed Aggregates.

(a) Segregation. Before acceptance testing, remix all aggregate segregated by transit or stockpiling.

(b) Stockpiling.

- Keep aggregates from different sources, with different gradings or with a significantly different specific gravity separated.
- Transport aggregate in a manner that insures uniform grading.
- Do not use aggregates that have become mixed with earth or foreign material.
- Stockpile or bin all washed aggregate produced or handled by hydraulic methods for 12 hours (minimum) before batching. Rail shipment exceeding 12 hours is acceptable for binning provided the car bodies permit free drainage.
- Provide additional stockpiling or binning in cases of high or non-uniform moisture.

1102.3 TEST METHODS.

Test aggregates according to the applicable provisions of **Section 1117.**

1102.4 PREQUALIFICATION.

Aggregates for concrete must be prequalified according to the requirements of **subsection 1101.02**.

1102.5 BASIS OF ACCEPTANCE.

The Engineer will accept aggregates for concrete base on the prequalification required by this specification, and the requirements of **subsection 1101.03**.

08-02-06 M&R (RAM & REK)

KANSAS DEPARTMENT OF TRANSPORTATION

SPECIAL PROVISION TO THE

STANDARD SPECIFICATIONS, 1990 EDITION

NOTE: This special provision is generally written in the imperative mood. The subject, "the *Contractor*" is implied. Also implied in this language are "*shall*", "*shall be*", or similar words and phrases. The word "*will*" generally pertains to decisions or actions` of the Kansas Department of Transportation.

Section 1102. Delete the entire Section and replace with this:

SECTION 1102

LOW CRACKING HIGH PERFORMANCE - AGGREGATES FOR CONCRETE

1102.1 DESCRIPTION.

This specification is for coarse aggregates, fine aggregates, and mixed aggregates (both coarse and fine material) for use in bridge deck construction.

1102.2 REQUIREMENTS.

a. Coarse Aggregate for Concrete.

(1) Composition. Provide coarse aggregate that is crushed or uncrushed gravel, chat, or crushed stone. (Consider calcite cemented sandstone, rhyolite, basalt and granite as crushed stone).

(2) Quality. The quality requirements for coarse aggregate for bridge decks are in **TABLE 1102-1**:

TABLE 1102-1 Quality Requirements for Coarse Aggregates for Bridge Decks

Concrete Classification	Soundness (min.)	Wear max.)	Absorption (max.)	Acid Insol. (min.)
Grade 3.5 (AE) (LC-HPC) [1] (Grade 24 (AE) (LC-HPC)) [1]	0.90	40	0.7	55

[1] Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) – Bridge Deck concrete with select coarse aggregate for wear and acid insolubility.

(3) Product Control.

(a) Deleterious Substances. Maximum allowed deleterious substances by weight are:

- Material passing the No. 200 (75 µm) sieve (KT-2)…….. 2.5%
- Shale or Shale-like material (KT-8) …………… …….. 0.5%
- Clay lumps and friable particles (KT-7)…………………..1.0%

- Sticks (wet) (KT-35)……………………………………0.1%
- Coal (AASHTO T 113)……………………………… 0.5%

(b) Uniformity of Supply. Designate or determine the fineness modulus (grading factor) according to the procedure listed in the Construction Manual Part V, Section 17 before delivery, or from the first 10 samples tested and accepted. Provide aggregate that is within ±0.20 of the average fineness modulus.

(4) Do not combine siliceous fine aggregate with siliceous coarse aggregate if neither meet the requirements of **subsection 1102.2c.(2)(a)**. Consider such fine material, regardless of proportioning, as a Basic Aggregate that must conform to the requirements in **subsection 1102.2c.**

(5) Handling Coarse Aggregates.

(a) Segregation. Before acceptance testing, remix all aggregate segregated by transportation or stockpiling operations.

(b) Stockpiling.

- Stockpile accepted aggregates in layers 3 to 5 feet (1.0 to 1.5 m) thick. Berm each layer so that aggregates do not "cone" down into lower layers.
- Keep aggregates from different sources, with different gradings, or with a significantly different specific gravity separated.
- Transport aggregate in a manner that insures uniform gradation.
- Do not use aggregates that have become mixed with earth or foreign material.
- Stockpile or bin all washed aggregate produced or handled by hydraulic methods for 12 hours (minimum) before batching. Rail shipment exceeding 12 hours is acceptable for binning provided the car bodies permit free drainage.
- Provide additional stockpiling or binning in cases of high or non-uniform moisture.

b. Fine Aggregates for Basic Aggregate in MA for Concrete.

(1) Composition.

(a) Type FA-A. Provide either singly or in combination natural occurring sand resulting from the disintegration of siliceous or calcareous rock, or manufactured sand produced by crushing predominately siliceous materials.

(b) Type FA-B. Provide fine granular particles resulting from the crushing of zinc and lead ores (Chat).

(2) Quality.

(a) Mortar strength and Organic Impurities. If the District Materials Engineer determines it is necessary, because of unknown characteristics of new sources or changes in existing sources, provide fine aggregates that comply with these requirements:

- Mortar Strength (Mortar Strength Test, KTMR-26). Compressive strength when combined with Type III (high early strength) cement:
  - At age 24 hours, minimum…………..100%*
  - At age 72 hours, minimum…………..100%*

  *Compared to strengths of specimens of the same proportions, consistency, cement and standard 20-30 Ottawa sand.
- Organic Impurities (Organic Impurities in Fine Aggregate for Concrete Test, AASHTO T 21). The color of the supernatant liquid is equal to or lighter than the reference standard solution.

(b) Hardening characteristics. Specimens made of a mixture of 3 parts FA-B and 1 part cement with sufficient water for molding will harden within 24 hours. There is no hardening requirement for FA-A.

(3) Product Control.

(a) Deleterious Substances.

- Type FA-A: Maximum allowed deleterious substances by weight are:
  - Material passing the No. 200 (75 µm) sieve (KT-2) …2.0%
  - Shale or Shale-like material (KT-8) …………………..…0.5%
  - Clay lumps and friable particles (KT-7)………..…… 1.0%
  - Sticks (wet) (KT-35)…………………...…………. .. 0.1%
- Type FA-B: Provide materials that are free of organic impurities, sulfates, carbonates, or alkali. Maximum allowed deleterious substances by weight are:
  - Material passing the No. 200 (75 µm) sieve (KT-2)… 2.0%
  - Clay lumps & friable particles (KT-7)………..… … 0.25%

(c) Uniformity of Supply. Designate or determine the fineness modulus (grading factor) according to the procedure listed in the Construction Manual Part V, Section 17 before delivery, or from the first 10 samples tested and accepted. Provide aggregate that is within ±0.20 of the average fineness modulus.

(4) Proportioning of Coarse and Fine Aggregate. Use a proven optimization method such as the Shilstone Method or the KU Mix Method.

Do not combine siliceous fine aggregate with siliceous coarse aggregate if neither meet the requirements of **subsection 1102.2c.(2)(a).** Consider such fine material, regardless of proportioning, as a Basic Aggregate and must conform to the requirements in **subsection 1102.2c.**

(5) Handling and Stockpiling Fine Aggregates.

- Keep aggregates from different sources, with different gradings or with a significantly different specific gravity separated.
- Transport aggregate in a manner that insures uniform grading.
- Do not use aggregates that have become mixed with earth or foreign material.
- Stockpile or bin all washed aggregate produced or handled by hydraulic methods for 12 hours (minimum) before batching. Rail shipment exceeding 12 hours is acceptable for binning provided the car bodies permit free drainage.
- Provide additional stockpiling or binning in cases of high or non-uniform moisture.

c. Mixed Aggregates for Concrete.

(1) Composition.

(a) Total Mixed Aggregate (TMA). A natural occurring, predominately siliceous aggregate from a single source that meets the Wetting & Drying Test (KTMR-23) and grading requirements.

(b) Mixed Aggregate. A combination of basic and coarse aggregates that meet the gradation requirements of Table 1102-3.

- Basic Aggregate (BA). Singly or in combination, a natural occurring, predominately siliceous aggregate that does not meet the grading requirements of Total Mixed Aggregate.

(c) Coarse Aggregate. Granite, crushed sandstone, chat, and gravel. Gravel that is not approved under 1102.2c.(2) may be used, but only with basic aggregate that meets the wetting and drying requirements of TMA.

(2) Quality.

(a) Total Mixed Aggregate.

- Soundness, minimum (KTMR-21) ……..…………0.90
- Wear, maximum (KTMR-25) ……………….….. 50%
- Wetting and Drying Test (KTMR-23) for Total Mixed Aggregate

  Concrete Modulus of Rupture:
  - At 60 days, minimum………………………….550 psi
  - At 365 days, minimum…..…………………..……550 psi

  Expansion:
  - At 180 days, maximum…………….…………0.050%
  - At 365 days, maximum……………….….……0.070%

Aggregates produced from the following general areas are exempt from the Wetting and Drying Test:

- Blue River Drainage Area.
- The Arkansas River from Sterling, west to the Colorado state line.
- The Neosho River from Emporia to the Oklahoma state line.

(b) Basic Aggregate.

- Retain 10% or more of the BA on the No. 8 (2.36 mm) sieve before adding the Coarse Aggregate. Aggregate with less than 10% retained on the No. 8 (2.36 mm) sieve is to be considered a Fine Aggregate described in S**ubsection 1103**. Provide material with less than 5% calcareous material retained on the ⅜" (9.5 mm) sieve.
- Soundness, minimum (KTMR-21)……………….0.90
- Wear, maximum (KTMR-25)……………….….. 50%
- Mortar strength and Organic Impurities. If the District Materials Engineer determines it is necessary, because of unknown characteristics of new sources or changes in existing sources, provide mixed aggregates that comply with these requirements:
  - Mortar Strength (Mortar Strength Test, KTMR-26). Compressive strength when combined with Type III (high early strength) cement:
    - At age 24 hours, minimum…………..100%*
    - At age 72 hours, minimum…………..100%*

      *Compared to strengths of specimens of the same proportions, consistency, cement and standard 20-30 Ottawa sand.
  - Organic Impurities (Organic Impurities in Fine Aggregate for Concrete Test, AASHTO T 21). The color of the supernatant liquid is equal to or lighter than the reference standard solution.

(3) Product Control.

(a) Size Requirement. Provide mixed aggregates that comply with the grading requirements in **TABLE 1102-3 & 1102-4**.

TABLE 1102-3 Grading Requirements for Mixed Aggregates for Concrete Bridge Decks and Barrier Rail

Type	Usage	Percent Retained on Individual Sieves - Square Mesh Sieves										
		1½ " (37.5 mm)	1" (25.0 mm)	3/4" (19.0 mm)	1/2" (12.5 mm)	3/8" (9.5 mm)	No. 4 (4.75 mm)	No. 8 (2.36 mm)	No. 16 (1.18 mm)	No. 30 (600 µm)	No. 50 (300 µm)	No. 100 150 µm)
MA-4	Optimized for LC-HPC Bridge Decks*	0	2-6	5-18	8-18	8-18	8-18	8-18	8-18	8-15	5-15	0-5

*Use a proven optimization method, such as the Shilstone Method or the KU Mix Method.

TABLE 1102-4 Grading Requirements for Mixed Aggregates for Concrete Corral Bridge Rail

Type	Usage	Percent Retained on Individual Sieves - Square Mesh Sieves										
		1½ " (37.5 mm)	1" (25.0 mm)	3/4" (19.0 mm)	1/2" (12.5 mm)	3/8" (9.5 mm)	No. 4 (4.75 mm)	No. 8 (2.36 mm)	No. 16 (1.18 mm)	No. 30 (600 µm)	No. 50 (300 µm)	No. 100 150 µm)
MA-4	Optimized for LC-HPC Bridge Rail*	0	0	2-6	8-20	8-20	8-20	8-20	8-20	5-15	5-15	0-6

*Use a proven optimization method, such as the Shilstone Method or the KU Mix Method.

(b) The adjusted gradation for Corral rail (Table 1102-4) is not necessary for Barrier rail (Table 1102-3).

(c) Deleterious Substances. Maximum allowed deleterious substances by weight are:

- Material passing the No. 200 (75 µm) sieve (KT-2)……….. 2.5%
- Shale or Shale-like material (KT-8)…………………..……. 0.5%
- Clay lumps and friable particles (KT-7)…………………1.0%
- Sticks (wet) (KT-35)………………………..…………… 0.1%
- Coal (AASHTO T 113)…..……………………..………. 0.5%

(d) Uniformity of Supply. Designate or determine the fineness modulus (grading factor) according to the procedure listed in the Construction Manual Part V, Section 17 before delivery, or from the first 10 samples tested and accepted. Provide aggregate that is within ±0.20 of the average fineness modulus.

(4) Handling Mixed Aggregates.

(a) Segregation. Before acceptance testing, remix all aggregate segregated by transit or stockpiling.

(b) Stockpiling.

- Keep aggregates from different sources, with different gradings or with a significantly different specific gravity separated.
- Transport aggregate in a manner that insures uniform grading.
- Do not use aggregates that have become mixed with earth or foreign material.
- Stockpile or bin all washed aggregate produced or handled by hydraulic methods for 12 hours (minimum) before batching. Rail shipment exceeding 12 hours is acceptable for binning provided the car bodies permit free drainage.
- Provide additional stockpiling or binning in cases of high or non-uniform moisture.

1102.3 TEST METHODS.

Test aggregates according to the applicable provisions of **Section 1117.**

1102.4 PREQUALIFICATION.

Aggregates for concrete must be prequalified according to the requirements of **subsection 1101.02**.

1102.5 BASIS OF ACCEPTANCE.

The Engineer will accept aggregates for concrete base on the prequalification required by this specification, and the requirements of **subsection 1101.03**.

09-28-06 M&R (RAM & REK)
5085

KANSAS DEPARTMENT OF TRANSPORTATION

SPECIAL PROVISION TO THE

STANDARD SPECIFICATIONS, 1990 EDITION

NOTE: This special provision is generally written in the imperative mood. The subject, "the *Contractor*" is implied. Also implied in this language are "*shall*", "*shall be*", or similar words and phrases. The word "*will*" generally pertains to decisions or actions` of the Kansas Department of Transportation.

Section 1102. Delete the entire Section and replace with this:

SECTION 1102

LOW CRACKING HIGH PERFORMANCE - AGGREGATES FOR CONCRETE

1102.1 DESCRIPTION.

This specification is for coarse aggregates, fine aggregates, and mixed aggregates (both coarse and fine material) for use in bridge deck construction.

1102.2 REQUIREMENTS.

a. Coarse Aggregate for Concrete.

(1) Composition. Provide coarse aggregate that is crushed or uncrushed gravel, chat, or crushed stone. (Consider calcite cemented sandstone, rhyolite, basalt and granite as crushed stone).

(2) Quality. The quality requirements for coarse aggregate for bridge decks are in **TABLE 1102-1**:

TABLE 1102-1 Quality Requirements for Coarse Aggregates for Bridge Decks

Concrete Classification	Soundness (min.)	Wear max.)	Absorption (max.)	Acid Insol. (min.)
Grade 3.5 (AE) (LC-HPC) [1] (Grade 24 (AE) (LC-HPC)) [1]	0.90	40	0.7	55

[1] Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) – Bridge Deck concrete with select coarse aggregate for wear and acid insolubility.

(3) Product Control.

(a) Deleterious Substances. Maximum allowed deleterious substances by weight are:

- Material passing the No. 200 (75 µm) sieve (KT-2)……. 2.5%
- Shale or Shale-like material (KT-8) …………………..0.5%
- Clay lumps and friable particles (KT-7)…………………..1.0%

- Sticks (wet) (KT-35) 0.1%
- Coal (AASHTO T 113)....................................0.5%

(b) Uniformity of Supply. Designate or determine the fineness modulus (grading factor) according to the procedure listed in the Construction Manual Part V, Section 17 before delivery, or from the first 10 samples tested and accepted. Provide aggregate that is within ±0.20 of the average fineness modulus.

(4) Do not combine siliceous fine aggregate with siliceous coarse aggregate if neither meet the requirements of **subsection 1102.2c.(2)(a)**. Consider such fine material, regardless of proportioning, as a Basic Aggregate that must conform to the requirements in **subsection 1102.2c.**

(5) Handling Coarse Aggregates.

(a) Segregation. Before acceptance testing, remix all aggregate segregated by transportation or stockpiling operations.

(b) Stockpiling.

- Stockpile accepted aggregates in layers 3 to 5 feet (1.0 to 1.5 m) thick. Berm each layer so that aggregates do not "cone" down into lower layers.
- Keep aggregates from different sources, with different gradings, or with a significantly different specific gravity separated.
- Transport aggregate in a manner that insures uniform gradation.
- Do not use aggregates that have become mixed with earth or foreign material.
- Stockpile or bin all washed aggregate produced or handled by hydraulic methods for 12 hours (minimum) before batching. Rail shipment exceeding 12 hours is acceptable for binning provided the car bodies permit free drainage.
- Provide additional stockpiling or binning in cases of high or non-uniform moisture.

b. Fine Aggregates for Basic Aggregate in MA for Concrete.

(1) Composition.

(a) Type FA-A. Provide either singly or in combination natural occurring sand resulting from the disintegration of siliceous or calcareous rock, or manufactured sand produced by crushing predominately siliceous materials.

(b) Type FA-B. Provide fine granular particles resulting from the crushing of zinc and lead ores (Chat).

(2) Quality.

(a) Mortar strength and Organic Impurities. If the District Materials Engineer determines it is necessary, because of unknown characteristics of new sources or changes in existing sources, provide fine aggregates that comply with these requirements:

- Mortar Strength (Mortar Strength Test, KTMR-26). Compressive strength when combined with Type III (high early strength) cement:
  - At age 24 hours, minimum…………..100%*
  - At age 72 hours, minimum…………..100%*

  *Compared to strengths of specimens of the same proportions, consistency, cement and standard 20-30 Ottawa sand.
- Organic Impurities (Organic Impurities in Fine Aggregate for Concrete Test, AASHTO T 21). The color of the supernatant liquid is equal to or lighter than the reference standard solution.

(b) Hardening characteristics. Specimens made of a mixture of 3 parts FA-B and 1 part cement with sufficient water for molding will harden within 24 hours. There is no hardening requirement for FA-A.

(3) Product Control.

(a) Deleterious Substances.

- Type FA-A: Maximum allowed deleterious substances by weight are:
  - Material passing the No. 200 (75 µm) sieve (KT-2) …2.0%
  - Shale or Shale-like material (KT-8) ………………..…0.5%
  - Clay lumps and friable particles (KT-7)………..….… 1.0%
  - Sticks (wet) (KT-35)………………………….....…. .. 0.1%
- Type FA-B: Provide materials that are free of organic impurities, sulfates, carbonates, or alkali. Maximum allowed deleterious substances by weight are:
  - Material passing the No. 200 (75 µm) sieve (KT-2)... 2.0%
  - Clay lumps & friable particles (KT-7)………….. … 0.25%

(c) Uniformity of Supply. Designate or determine the fineness modulus (grading factor) according to the procedure listed in the Construction Manual Part V, Section 17 before delivery, or from the first 10 samples tested and accepted. Provide aggregate that is within ±0.20 of the average fineness modulus.

(4) Proportioning of Coarse and Fine Aggregate. Use a proven optimization method such as the Shilstone Method or the KU Mix Method.

Do not combine siliceous fine aggregate with siliceous coarse aggregate if neither meet the requirements of **subsection 1102.2c.(2)(a).** Consider such fine material, regardless of proportioning, as a Basic Aggregate and must conform to the requirements in **subsection 1102.2c.**

(5) Handling and Stockpiling Fine Aggregates.

- Keep aggregates from different sources, with different gradings or with a significantly different specific gravity separated.
- Transport aggregate in a manner that insures uniform grading.
- Do not use aggregates that have become mixed with earth or foreign material.
- Stockpile or bin all washed aggregate produced or handled by hydraulic methods for 12 hours (minimum) before batching. Rail shipment exceeding 12 hours is acceptable for binning provided the car bodies permit free drainage.
- Provide additional stockpiling or binning in cases of high or non-uniform moisture.

c. Mixed Aggregates for Concrete.
(1) Composition.
(a) Total Mixed Aggregate (TMA). A natural occurring, predominately siliceous aggregate from a single source that meets the Wetting & Drying Test (KTMR-23) and grading requirements.
(b) Mixed Aggregate. A combination of basic and coarse aggregates that meet the gradation requirements of Table 1102-3.

- Basic Aggregate (BA). Singly or in combination, a natural occurring, predominately siliceous aggregate that does not meet the grading requirements of Total Mixed Aggregate.

(c) Coarse Aggregate. Granite, crushed sandstone, chat, and gravel. Gravel that is not approved under 1102.2c.(2) may be used, but only with basic aggregate that meets the wetting and drying requirements of TMA.
(2) Quality.
(a) Total Mixed Aggregate.

- Soundness, minimum (KTMR-21) ……..…………0.90
- Wear, maximum (KTMR-25) ………………..….. 50%
- Wetting and Drying Test (KTMR-23) for Total Mixed Aggregate
  Concrete Modulus of Rupture:
  - At 60 days, minimum………………………….550 psi
  - At 365 days, minimum…..…………………..……550 psi
  Expansion:
  - At 180 days, maximum…………….…………0.050%
  - At 365 days, maximum……………….…….0.070%

Aggregates produced from the following general areas are exempt from the Wetting and Drying Test:

- Blue River Drainage Area.
- The Arkansas River from Sterling, west to the Colorado state line.
- The Neosho River from Emporia to the Oklahoma state line.

(b) Basic Aggregate.

- Retain 10% or more of the BA on the No. 8 (2.36 mm) sieve before adding the Coarse Aggregate. Aggregate with less than 10% retained on the No. 8 (2.36 mm) sieve is to be considered a Fine Aggregate described in S**ubsection 1103**. Provide material with less than 5% calcareous material retained on the ⅜" (9.5 mm) sieve.
- Soundness, minimum (KTMR-21)……………….0.90
- Wear, maximum (KTMR-25)…………………….. 50%
- Mortar strength and Organic Impurities. If the District Materials Engineer determines it is necessary, because of unknown characteristics of new sources or changes in existing sources, provide mixed aggregates that comply with these requirements:
  - Mortar Strength (Mortar Strength Test, KTMR-26). Compressive strength when combined with Type III (high early strength) cement:
    - At age 24 hours, minimum…………..100%*
    - At age 72 hours, minimum…………..100%*

      *Compared to strengths of specimens of the same proportions, consistency, cement and standard 20-30 Ottawa sand.
  - Organic Impurities (Organic Impurities in Fine Aggregate for Concrete Test, AASHTO T 21). The color of the supernatant liquid is equal to or lighter than the reference standard solution.

(3) Product Control.

(a) Size Requirement. Provide mixed aggregates that comply with the grading requirements in **TABLE 1102-3 & 1102-4**.

TABLE 1102-3 Grading Requirements for Mixed Aggregates for Concrete Bridge Decks and Barrier Rail

Type	Usage	Percent Retained on Individual Sieves - Square Mesh Sieves										
		1½ " (37.5 mm)	1" (25.0 mm)	3/4" (19.0 mm)	1/2" (12.5 mm)	3/8" (9.5 mm)	No. 4 (4.75 mm)	No. 8 (2.36 mm)	No. 16 (1.18 mm)	No. 30 (600 µm)	No. 50 (300 µm)	No. 100 150 µm)
MA-4	Optimized for LC-HPC Bridge Decks*	0	2-6	5-18	8-18	8-18	8-18	8-18	8-18	8-15	5-15	0-5

*Use a proven optimization method, such as the Shilstone Method or the KU Mix Method.

TABLE 1102-4 Grading Requirements for Mixed Aggregates for Concrete Corral Bridge Rail

Type	Usage	Percent Retained on Individual Sieves - Square Mesh Sieves										
		1½ " (37.5 mm)	1" (25.0 mm)	3/4" (19.0 mm)	1/2" (12.5 mm)	3/8" (9.5 mm)	No. 4 (4.75 mm)	No. 8 (2.36 mm)	No. 16 (1.18 mm)	No. 30 (600 µm)	No. 50 (300 µm)	No. 100 150 µm)
MA-4	Optimized for LC-HPC Bridge Rail*	0	0	2-6	8-20	8-20	8-20	8-20	8-20	5-15	5-15	0-6

*Use a proven optimization method, such as the Shilstone Method or the KU Mix Method.

(b) The adjusted gradation for Corral rail (Table 1102-4) is not necessary for Barrier rail (Table 1102-3).

(c) Deleterious Substances. Maximum allowed deleterious substances by weight are:

- Material passing the No. 200 (75 µm) sieve (KT-2)……….. 2.5%
- Shale or Shale-like material (KT-8)…………………..……. 0.5%
- Clay lumps and friable particles (KT-7)…………………1.0%
- Sticks (wet) (KT-35)………………………..…………… 0.1%
- Coal (AASHTO T 113)…..……………………..………. 0.5%

(d) Uniformity of Supply. Designate or determine the fineness modulus (grading factor) according to the procedure listed in the Construction Manual Part V, Section 17 before delivery, or from the first 10 samples tested and accepted. Provide aggregate that is within ±0.20 of the average fineness modulus.

(4) Handling Mixed Aggregates.

(a) Segregation. Before acceptance testing, remix all aggregate segregated by transit or stockpiling.

(b) Stockpiling.

- Keep aggregates from different sources, with different gradings or with a significantly different specific gravity separated.
- Transport aggregate in a manner that insures uniform grading.
- Do not use aggregates that have become mixed with earth or foreign material.
- Stockpile or bin all washed aggregate produced or handled by hydraulic methods for 12 hours (minimum) before batching. Rail shipment exceeding 12 hours is acceptable for binning provided the car bodies permit free drainage.
- Provide additional stockpiling or binning in cases of high or non-uniform moisture.

1102.3 TEST METHODS.

Test aggregates according to the applicable provisions of **Section 1117.**

1102.4 PREQUALIFICATION.

Aggregates for concrete must be prequalified according to the requirements of **subsection 1101.02**.

1102.5 BASIS OF ACCEPTANCE.

The Engineer will accept aggregates for concrete base on the prequalification required by this specification, and the requirements of **subsection 1101.03**.

09-28-06 M&R (RAM & REK)
7359

LCHPC-2 LOW CRACKING HIGH PERFORMANCE CONCRETE- AGGREGATES

LCHPC-2.1 DESCRIPTION.

This specification is for coarse aggregates, fine aggregates, and mixed aggregates (both coarse and fine material) for use in bridge deck construction.

LCHPC-2.2 REQUIREMENTS.

a. Coarse Aggregate for Concrete.

(1) Composition. Provide coarse aggregates that are crushed granite.

(2) Quality. The quality requirements for coarse aggregates test results shall not exceed the following percentages by weight:

AASHTO T103 Soundness by Freeze/Thaw 50 Cycles	Max. Allowable %
3/4 - 3/8	1.0%
3/8 - #4	2.0%
ASTM C127 Absorption%	0.5%
ASTM C131 LA Abrasion % Loss	28.0%

(3) Product Control.

(a) Deleterious Substances. Maximum allowed deleterious substances by weight are:

- Material passing the No. 200 (75 μm) sieve (KT-2)............~~2.5%~~ 0.5%
- Shale or Shale-like material (KT-8).................................... 0.5%
- Clay lumps and friable particles (KT-7).............................~~1.0%~~ 0.3%
- Sticks (wet) (KT-35)... 0.1%
- Coal (AASHTO T 113)..~~0.5%~~ 0.05%
- Sum of all deleterious 1.0%

(c) Uniformity of Supply. Designate or determine the fineness modulus (grading factor) according to the procedure listed in the Construction Manual Part V, Section 17 before delivery, or from the first 10 samples tested and accepted. Provide aggregate that is within ±0.20 of the average fineness modulus.

(4) Handling Coarse Aggregates.

(a) Segregation. Before acceptance testing, remix all aggregate segregated by transportation or stockpiling operations.

(b) Stockpiling.

- Stockpile accepted aggregates in layers 3 to 5 feet (1.0 to 1.5 m) thick. Berm each layer so that aggregates do not "cone" down into lower layers.
- Keep aggregates from different sources, with different gradings, or with a significantly different specific gravity separated.
- Transport aggregate in a manner that insures uniform gradation.
- Do not use aggregates that have become mixed with earth or foreign material.
- Stockpile or bin all washed aggregate produced or handled by hydraulic methods for 12 hours (minimum) before batching. Rail shipment exceeding 12 hours is acceptable for binning provided the car bodies permit free drainage.

- Provide additional stockpiling or binning in cases of high or non-uniform moisture.

b. Fine Aggregates for Basic Aggregate in MA for Concrete.

(1) Composition.

(a) Type FA-A. Provide either singly or in combination with natural occurring sand from the Kansas River resulting from the disintegration of siliceous or calcareous rock, or manufactured sand produced by crushing predominately siliceous materials.

(2) Quality.

(a) Mortar strength and Organic Impurities. If the Engineer determines it is necessary, because of unknown characteristics of new sources or changes in existing sources, provide fine aggregates that comply with these requirements:

- Mortar Strength (Mortar Strength Test, KTMR-26). Compressive strength when combined with Type III (high early strength) cement:
  - At age 24 hours, minimum..............100%*
  - At age 72 hours, minimum..............100%*

  *Compared to strengths of specimens of the same proportions, consistency, cement and standard 20-30 Ottawa sand.
- Organic Impurities (Organic Impurities in Fine Aggregate for Concrete Test, AASHTO T 21). The color of the supernatant liquid is equal to or lighter than the reference standard solution.

(b) Hardening characteristics. Specimens made of a mixture of 3 parts FA-B and 1 part cement with sufficient water for molding will harden within 24 hours. There is no hardening requirement for FA-A.

(3) Product Control.

(a) Deleterious Substances.

- Type FA-A: Maximum allowed deleterious substances by weight are:
  - Material passing the No. 200 (75 μm) sieve (KT-2)............2.0%
  - Shale or Shale-like material (KT-8) 0.5%
  - Clay lumps and friable particles (KT-7)........................... 1.0%
  - Sticks (wet) (KT-35).. 0.1%
- Type FA-B: Provide materials that are free of organic impurities, sulfates, carbonates, or alkali. Maximum allowed deleterious substances by weight are:
  - Material passing the No. 200 (75 μm) sieve (KT-2)........... 2.0%
  - Clay lumps & friable particles (KT-7)........................... 0.25%

(c) Uniformity of Supply. Designate or determine the fineness modulus (grading factor) according to the procedure listed in the Construction Manual Part V, Section 17 before delivery, or from the first 10 samples tested and accepted. Provide aggregate that is within ±0.20 of the average fineness modulus.

(4) Proportioning of Coarse and Fine Aggregate. Use a proven optimization method such as the Shilstone Method or the KU Mix Method. Regardless of the method, the maximum percentage of natural sand shall not exceed 45%.

(5) Handling and Stockpiling Fine Aggregates.

- Keep aggregates from different sources, with different gradings or with a significantly different specific gravity separated.
- Transport aggregate in a manner that insures uniform grading.
- Do not use aggregates that have become mixed with earth or foreign material.
- Stockpile or bin all washed aggregate produced or handled by hydraulic methods for 12 hours (minimum) before batching. Rail shipment exceeding 12 hours is acceptable for binning provided the car bodies permit free drainage.
- Provide additional stockpiling or binning in cases of high or non-uniform moisture.

c. Grading Requirements for Blended Aggregates

Provide blended aggregates that comply with the grading requirements in **TABLES 1 (LCHPC-2) & 2 (LCHPC-2).**

TABLE 1 (LCHPC-2) Grading Requirements for Blended Aggregates for Concrete Bridge Decks and Barrier Rail

Type	Usage	Percent Retained on Individual Sieves - Square Mesh Sieves										
		1½" (37.5 mm)	1" (25.0 mm)	3/4" (19.0 mm)	1/2" (12.5 mm)	3/8" (9.5 mm)	No. 4 (4.75 mm)	No. 8 (2.36 mm)	No. 16 (1.18 mm)	No. 30 (600 µm)	No. 50 (300 µm)	No. 100 150 µm)
MA-4	Optimized for LC-HPC Bridge Decks*	0	2-6	5-18	8-18	8-18	8-18	8-18	8-18	8-15	5-15	0-5

*Use a proven optimization method, such as the Shilstone Method or the KU Mix Method.

TABLE 2 (LCHPC-2)Grading Requirements for Blended Aggregates for Concrete Corral Bridge Rail

Type	Usage	Percent Retained on Individual Sieves - Square Mesh Sieves										
		1½" (37.5 mm)	1" (25.0 mm)	3/4" (19.0 mm)	1/2" (12.5 mm)	3/8" (9.5 mm)	No. 4 (4.75 mm)	No. 8 (2.36 mm)	No. 16 (1.18 mm)	No. 30 (600 µm)	No. 50 (300 µm)	No. 100 150 µm)
MA-4	Optimized for LC-HPC Bridge Rail*	0	0	2-6	8-20	8-20	8-20	8-20	8-20	5-15	5-15	0-6

*Use a proven optimization method, such as the Shilstone Method or the KU Mix Method.

LCHPC-2.3 TEST METHODS.

Test aggregates according to the applicable provisions of **Section 1117.**

LCHPC-2.4 PREQUALIFICATION.

Aggregates for concrete must be prequalified according to the requirements of **subsection 1101.02**.

LCHPC-2.5 BASIS OF ACCEPTANCE.

The Engineer will accept aggregates on the prequalification required by this specification, and the requirements of **subsection 1101.03**.

KANSAS DEPARTMENT OF TRANSPORTATION

SPECIAL PROVISION TO THE

STANDARD SPECIFICATIONS, 2007 EDITION

Add a new SECTION to DIVISION 1100:

LOW-CRACKING HIGH-PERFORMANCE CONCRETE – AGGREGATES

1.0 DESCRIPTION

This specification is for coarse aggregates, fine aggregates, and mixed aggregates (both coarse and fine material) for use in bridge deck construction.

2.0 REQUIREMENTS

a. Coarse Aggregates for Concrete.

(1) Composition. Provide coarse aggregate that is crushed or uncrushed gravel, chat, or crushed stone. (Consider calcite cemented sandstone, rhyolite, basalt and granite as crushed stone

(2) Quality. The quality requirements for coarse aggregate for bridge decks are in **TABLE 1-1**:

TABLE 1-1: QUALITY REQUIREMENTS FOR COARSE AGGREGATES FOR BRIDGE DECK

Concrete Classification	Soundness (min.)	Wear (max.)	Absorption (max.)	Acid Insol. (min.)
Grade 3.5 (AE) (LC-HPC) [1]	0.90	40	0.7	55

[1] Grade 3.5 (AE) (LC-HPC) – Bridge Deck concrete with select coarse aggregate for wear and acid insolubility.

(3) Product Control.

(a) Deleterious Substances. Maximum allowed deleterious substances by weight are:

- Material passing the No. 200 sieve (KT-2)......................... 2.5%
- Shale or Shale-like material (KT-8).................................... 0.5%
- Clay lumps and friable particles (KT-7)............................. 1.0%
- Sticks (wet) (KT-35)... 0.1%
- Coal (AASHTO T 113).. 0.5%

(b) Uniformity of Supply. Designate or determine the fineness modulus (grading factor) according to the procedure listed in the Construction Manual Part V, Section 17 before delivery, or from the first 10 samples tested and accepted. Provide aggregate that is within ±0.20 of the average fineness modulus.

(4) Do not combine siliceous fine aggregate with siliceous coarse aggregate if neither meet the requirements of **subsection 2.0c.(2)(a)**. Consider such fine material, regardless of proportioning, as a Basic Aggregate that must conform to **subsection 2.0c**.

(5) Handling Coarse Aggregates.

(a) Segregation. Before acceptance testing, remix all aggregate segregated by transportation or stockpiling operations.

(b) Stockpiling.

- Stockpile accepted aggregates in layers 3 to 5 feet thick. Berm each layer so that aggregates do not "cone" down into lower layers.
- Keep aggregates from different sources, with different gradings, or with a significantly different specific gravity separated.
- Transport aggregate in a manner that insures uniform gradation.
- Do not use aggregates that have become mixed with earth or foreign material.
- Stockpile or bin all washed aggregate produced or handled by hydraulic methods for 12 hours (minimum) before batching. Rail shipment exceeding 12 hours is acceptable for binning provided the car bodies permit free drainage.
- Provide additional stockpiling or binning in cases of high or non-uniform moisture.

b. Fine Aggregates for Basic Aggregate in MA for Concrete.

(1) Composition.

(a) Type FA-A. Provide either singly or in combination natural occurring sand resulting from the disintegration of siliceous or calcareous rock, or manufactured sand produced by crushing predominately siliceous materials.

(b) Type FA-B. Provide fine granular particles resulting from the crushing of zinc and lead ores (Chat).

(2) Quality.

(a) Mortar strength and Organic Impurities. If the District Materials Engineer determines it is necessary, because of unknown characteristics of new sources or changes in existing sources, provide fine aggregates that comply with these requirements:

- Mortar Strength (Mortar Strength Test, KTMR-26). Compressive strength when combined with Type III (high early strength) cement:
  - At age 24 hours, minimum…………..100%*
  - At age 72 hours, minimum…………..100%*

  *Compared to strengths of specimens of the same proportions, consistency, cement and standard 20-30 Ottawa sand.
- Organic Impurities (Organic Impurities in Fine Aggregate for Concrete Test, AASHTO T 21). The color of the supernatant liquid is equal to or lighter than the reference standard solution.

(b) Hardening characteristics. Specimens made of a mixture of 3 parts FA-B and 1 part cement with sufficient water for molding will harden within 24 hours. There is no hardening requirement for FA-A.

(3) Product Control.

(a) Deleterious Substances.

- Type FA-A: Maximum allowed deleterious substances by weight are:
  - Material passing the No. 200 sieve (KT-2)………..…2.0%
  - Shale or Shale-like material (KT-8) …………………0.5%
  - Clay lumps and friable particles (KT-7)………..……1.0%
  - Sticks (wet) (KT-35)…………………………...……0.1%
- Type FA-B: Provide materials that are free of organic impurities, sulfates, carbonates, or alkali. Maximum allowed deleterious substances by weight are:
  - Material passing the No. 200 sieve (KT-2)………….2.0%
  - Clay lumps & friable particles (KT-7)………………0.25%

(c) Uniformity of Supply. Designate or determine the fineness modulus (grading factor) according to the procedure listed in the Construction Manual Part V, Section 17 before delivery, or from the first 10 samples tested and accepted. Provide aggregate that is within ±0.20 of the average fineness modulus.

(4) Proportioning of Coarse and Fine Aggregate. Use a proven optimization method such as the Shilstone Method or the KU Mix Method.

Do not combine siliceous fine aggregate with siliceous coarse aggregate if neither meet the requirements of **subsection 2.0c.(2)(a)**. Consider such fine material, regardless of proportioning, as a Basic Aggregate and must conform to the requirements in **subsection 2.0c**.

(5) Handling and Stockpiling Fine Aggregates.

- Keep aggregates from different sources, with different gradings or with a significantly different specific gravity separated.
- Transport aggregate in a manner that insures uniform grading.
- Do not use aggregates that have become mixed with earth or foreign material.

- Stockpile or bin all washed aggregate produced or handled by hydraulic methods for 12 hours (minimum) before batching. Rail shipment exceeding 12 hours is acceptable for binning provided the car bodies permit free drainage.
- Provide additional stockpiling or binning in cases of high or non-uniform moisture.

c. Mixed Aggregates for Concrete.

(1) Composition.

(a) Total Mixed Aggregate (TMA). A natural occurring, predominately siliceous aggregate from a single source that meets the Wetting & Drying Test (KTMR-23) and grading requirements.

(b) Mixed Aggregate. A combination of basic and coarse aggregates that meet **TABLE 1-2**.

- Basic Aggregate (BA). Singly or in combination, a natural occurring, predominately siliceous aggregate that does not meet the grading requirements of Total Mixed Aggregate.

(c) Coarse Aggregate. Granite, crushed sandstone, chat, and gravel. Gravel that is not approved under **subsection 2.0c.(2)** may be used, but only with basic aggregate that meets the wetting and drying requirements of TMA.

(2) Quality.

(a) Total Mixed Aggregate.

- Soundness, minimum (KTMR-21) ………………0.90
- Wear, maximum (KTMR-25) ……………………50%
- Wetting and Drying Test (KTMR-23) for Total Mixed Aggregate

  Concrete Modulus of Rupture:
  - At 60 days, minimum………………………….550 psi
  - At 365 days, minimum……………………….…550 psi

  Expansion:
  - At 180 days, maximum………………………..0.050%
  - At 365 days, maximum…………………………0.070%

  Aggregates produced from the following general areas are exempt from the Wetting and Drying Test:

  - Blue River Drainage Area.
  - The Arkansas River from Sterling, west to the Colorado state line.
  - The Neosho River from Emporia to the Oklahoma state line.

(b) Basic Aggregate.

- Retain 10% or more of the BA on the No. 8 sieve before adding the Coarse Aggregate. Aggregate with less than 10% retained on the No. 8 sieve is to be considered a Fine

Aggregate described in **subsection 2.0b**. Provide material with less than 5% calcareous material retained on the ⅜" sieve.

- Soundness, minimum (KTMR-21)……………….0.90
- Wear, maximum (KTMR-25)……………….……50%
- Mortar strength and Organic Impurities. If the District Materials Engineer determines it is necessary, because of unknown characteristics of new sources or changes in existing sources, provide mixed aggregates that comply with these requirements:
  - Mortar Strength (Mortar Strength Test, KTMR-26). Compressive strength when combined with Type III (high early strength) cement:
    - At age 24 hours, minimum…………..100%*
    - At age 72 hours, minimum…………..100%*

    *Compared to strengths of specimens of the same proportions, consistency, cement and standard 20-30 Ottawa sand.
  - Organic Impurities (Organic Impurities in Fine Aggregate for Concrete Test, AASHTO T 21). The color of the supernatant liquid is equal to or lighter than the reference standard solution.

(3) Product Control.

(a) Size Requirement. Provide mixed aggregates that comply with the grading requirements in **TABLE 1-2**.

TABLE 1-2: GRADING REQUIREMENTS FOR MIXED AGGREGATES FOR CONCRETE BRIDGE DECKS

Type	**Usage**	**Percent Retained on Individual Sieves - Square Mesh Sieves**										
		1½"	**1"**	**3/4"**	**1/2"**	**3/8"**	**No. 4**	**No. 8**	**No. 16**	**No. 30**	**No. 50**	**No. 100**
MA-4	Optimized for LC-HPC Bridge Decks*	0	2-6	5-18	8-18	8-18	8-18	8-18	8-18	8-15	5-15	0-5

*Use a proven optimization method, such as the Shilstone Method or the KU Mix Method.

Note: Manufactured sands used to obtain optimum gradations have caused difficulties in pumping, placing or finishing. Natural coarse sands and pea gravels used to obtain optimum gradations have worked well in concretes that were pumped.

(b) Deleterious Substances. Maximum allowed deleterious substances by weight are:

- Material passing the No. 200 sieve (KT-2)……………..….. 2.5%
- Shale or Shale-like material (KT-8)…………………..……. 0.5%

- Clay lumps and friable particles (KT-7)…………………… 1.0%
- Sticks (wet) (KT-35)…………………………..…………… 0.1%
- Coal (AASHTO T 113)…..……………………..………. 0.5%

(c) Uniformity of Supply. Designate or determine the fineness modulus (grading factor) according to the procedure listed in the Construction Manual Part V, Section 17 before delivery, or from the first 10 samples tested and accepted. Provide aggregate that is within ±0.20 of the average fineness modulus.

(4) Handling Mixed Aggregates.

(a) Segregation. Before acceptance testing, remix all aggregate segregated by transit or stockpiling.

(b) Stockpiling.

- Keep aggregates from different sources, with different gradings or with a significantly different specific gravity separated.
- Transport aggregate in a manner that insures uniform grading.
- Do not use aggregates that have become mixed with earth or foreign material.
- Stockpile or bin all washed aggregate produced or handled by hydraulic methods for 12 hours (minimum) before batching. Rail shipment exceeding 12 hours is acceptable for binning provided the car bodies permit free drainage.
- Provide additional stockpiling or binning in cases of high or non-uniform moisture.

3.0 TEST METHODS

Test aggregates according to the applicable provisions of **SECTION 1117**.

4.0 PREQUALIFICATION

Aggregates for concrete must be prequalified according to **subsection 1101.2**.

5.0 BASIS OF ACCEPTANCE

The Engineer will accept aggregates for concrete base on the prequalification required by this specification, and **subsection 1101.4**.

07-29-09 LAL
07-PS0165

C.3 CONCRETE

The seven versions of the concrete special provisions for Phase 1 construction and the Phase 2 special provisions follow, including: 90M-7181, 90M-7275, 90M-7295, 90M-7338, 90P-5095, 90M-7360, LCHPC-1, and 07-LC-HPC-Conc.

KANSAS DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION TO THE
STANDARD SPECIFICATIONS 1990 EDITION

NOTE: This special provision is generally written in the imperative mood. The subject, "the *Contractor*" is implied. Also implied in this language are "*shall*", "*shall be*", or similar words and phrases. The word "*will*" generally pertains to decisions or actions` of the Kansas Department of Transportation.

Section 402. Delete the Section and replace with this:

SECTION 402

LOW CRACKING HIGH PERFORMANCE - CONCRETE

402.1 DESCRIPTION
Provide the grades of concrete specified in the Contract Documents.

402.2 MATERIALS
Provide coarse, fine, and mixed aggregates that comply with the requirements of **Special Provision 90M-7182**.

Provide admixtures that comply with the requirements of **Section 1400**.

Provide cement that complies with the requirements of **Special Provision 90M-7183**.

Provide water for concrete that complies with the requirements of **Section 2400**.

402.3 CONCRETE MIX DESIGN
a. General. The Contractor (or a prospective bidder) may contact the District Materials Engineer or the Bureau of Materials and Research for any available information to help determine approximate proportions which will produce concrete having the required characteristics.

The Contractor is responsible for the actual proportions of the concrete mix. If the Contractor requests (in writing), the Engineer will assist in the design of the concrete mix. A copy of the final design is to be submitted to the District Materials Engineer and Bureau of Materials and Research.

Design the concrete mixes specified in the Contract Documents. Design concrete mixes that comply with these requirements:

b. Air-Entrained Concrete for Bridge Decks. Design air-entrained concrete for structures according to these requirements:

TABLE 402-1, Air-Entrained Concrete for Bridge Decks

Grade of Concrete Type of Aggregate (Section 1100)	lb. (kg) of Cement per cu yd (cu m) of Concrete, min/max	lb (kg) of Water per lb (kg) of Cement, max*	Designated Air Content Percent by Volume**
Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC))			
MA-4	522 (310)/ 563(334)	0.45	8.0 ± 1.0

*Maximum limit of lb. (kg) of water per lb. (kg) of cement includes free water in aggregates, but excludes water of absorption of the aggregates.
** Concrete with an air content less than 6.5% or greater than 9.5% shall be rejected.
NOTE: For Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete, the total volume of water and cement shall not exceed 27% of the mix.

c. Portland Cement. Select the type of portland cement specified in the Contract Documents. No mineral admixtures are permitted for Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete.

d. Design Air Content. Use the middle of the specified air content range for the design of air-entrained concrete.

e. Admixtures for Acceleration, Air-Entraining, Plasticizing, Set Retardation, and Water Reduction. Use the dosages recommended by the admixture manufacturers. Incorporate and mix the admixtures into the concrete mixtures according to the manufacturer's recommendations.

Determine the quantity of each admixture for the concrete mix design.

If another admixture is added to an air-entrained concrete mixture, determine if it is necessary to adjust the air-entraining admixture dosage to maintain the specified air content.

Admixtures containing chloride ion (CL) in excess of 0.1 percent by mass of the admixture shall not be used in Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete.

(1) Accelerating Admixture. If specified in the Contract Documents, or in situations that involve contact with reinforcing steel and require early strength development to expedite opening to traffic, a non-chloride accelerator may be appropriate. The Engineer may approve the use of a Type C or E accelerating admixture.

(2) Air-Entraining Admixture. If specified, use air-entraining admixture in the concrete mixture.

If the concrete mixture also contains a plasticizing or a water reducing, high range admixture, use only a vinsol resin or tall oil based air-entraining admixture.

(3) Plasticizing Admixture. Include a batching sequence in the concrete mix design. Consider the location of the concrete plant in relation to the job site, and identify the approximate quantity, when and at what location the plasticizing admixture is added to the concrete mixture. Do not add water after the plasticizing admixture is added to the concrete mixture.

Manufacturers of plasticizing admixtures may recommend mixing revolutions beyond the limits specified in **subsection 402.5**. If necessary, address the additional mixing revolutions (the Engineer will allow up to 60 additional revolutions) in the concrete mix design.

Accomplish slump control in the field by redosing. If time and temperature limits are not exceeded, and if at least 30 mixing revolutions remain, the Engineer will allow redosing with up to 50 percent of the original dose.

(4) Water Reduction and Set Retardation. If unfavorable weather or other conditions adversely affect the placing and finishing properties of the concrete mix, the Engineer may allow the use of water reducing and set retarding admixtures. If the Engineer approves the use of water reducing and set retarding admixtures, their continued use depends on their performance. It is the Contractor's responsibility to insure that the admixtures will work as intended without detrimental effects.

(5) Adjust the mix designs during the course of the work when necessary to ensure compliance with the specified fresh and hardened concrete properties. Only permit such modifications after trial batches to demonstrate that the adjusted mix design will result in concrete that complies with the specified concrete properties.

The Engineer will allow adjustments to the dose rate of air entraining, water-reducing and retarding chemical admixtures to compensate for environmental changes during placement without a new concrete mix design or trial batch.

f. Designated Slump. Designate a slump for each concrete mix design that is within these limits:

TABLE 402-2, Designated Slump

Type of Work:	**Designated Slump in. (mm)**	**Maximum Allowable Slump in. (mm)**
Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC))	1 ½ - 3 (36-75)	4 (100)

NOTE: When high range water reducing admixtures are used with Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete mixtures, **Table 402-2** slump limits shall not be exceeded.

g. Approval of Concrete Mix Designs. Submit all concrete mix designs to the Engineer and the Research Development Engineer for review and approval. Submit completed volumetric mix designs on KDOT Form No. 694 (or other forms approved by the District Materials Engineer).

Do not place any concrete on the Project until the Engineer approves the concrete mix designs, trial batch, and trial slab. Once the Engineer approves the concrete mix design, do not make changes without the Engineer's approval (see Section 402.5b).

402.4 REQUIREMENTS FOR COMBINED MATERIALS.

a. Measurements for Proportioning Materials.

(1) Cement. Measure cement as packed by the manufacturer. A sack of cement is considered as 0.04 cubic yards (0.03 cu m) weighing 94 pounds (42.6 kg) net. Measure bulk cement by weight. In either case, the measurement must be accurate to within 0.5 percent throughout the range of use.

(2) Water. Measure the mixing water by weight or by volume. In either case the measurement must be accurate to within 1 percent throughout the range of use.

(3) Aggregates. Measure the aggregates by weight. The measurement must be accurate to within 0.5 percent throughout the range of use.

(4) Admixtures. Measure liquid admixtures by weight or volume. If liquid admixtures are used in small quantities in proportion to the cement as in the case of air-entraining agents, use readily adjustable mechanical dispensing equipment capable of being set to deliver the required quantity and to cut off the flow automatically when this quantity is discharged. The measurement must be accurate to within 3 percent of the quantity required.

b. Testing of Aggregates. Testing Aggregates at the Batch Site. Provide the Engineer with reasonable facilities at the batch site for obtaining samples of the aggregates. Provide adequate and safe laboratory facilities at the batch site that will allow the Engineer to test the aggregates for compliance with the specified requirements.

The Department will sample and test aggregates from each source to determine their compliance with specifications. Batching of the concrete mixture is not permitted until the Engineer has determined that the aggregates comply with the specifications. The Department will conduct the sampling at the batching site, and test the samples according to the Frequency Testing Chart in Part V of the KDOT Construction Manual. For QC/QA Contracts, the Contractor will determine testing intervals within the specified minimum frequency.

After initial testing is complete and the Engineer has determined that the aggregate process control is satisfactory, use the aggregates concurrently with sampling and testing as long as tests indicate compliance with specifications. During the batching operations, sample the aggregates as near the point of batching as feasible. Sample from the stream as the storage bins or weigh hoppers are loaded. If samples cannot be reasonably taken from the stream, take them from approved stockpiles. If test results indicate that an aggregate does not comply with specifications, cease concrete production using that aggregate. Unless a tested and approved stockpile for that aggregate is available at the batch plant, do not use any additional aggregate from that source and specified grading until subsequent sampling and testing of that aggregate indicate compliance with specifications. When tests are completed and the Engineer is satisfied that process control is again adequate, production of concrete using aggregates sampled and tested concurrently with production may resume.

c. Handling of Materials.

(1) Approved stockpiles are permitted only at the batch plant and only for small concrete placements or for the purpose of maintaining concrete production. Mark the approved stockpile with an "Approved Materials" sign. Provide a suitable stockpile area at the batch plant so that aggregates are stored without detrimental segregation or contamination. Unless otherwise approved by the Engineer, no more than 250 tons (Mg) of coarse aggregate and no more than 250 tons (Mg) of fine aggregate tested and approved by the Engineer may be stockpiled at the plant. If mixed aggregate is used, limit the approved stockpile to 500 tons (Mg), the size of each being proportional to the amount of each aggregate to be used in the mix.

Load aggregates into the mixer in such a manner that no material foreign to the concrete or material capable of changing the desired proportions is included. In the event 2 or more sizes or types of coarse or fine aggregates are used on the same project, only 1 size or type of each aggregate may be used on 1 continuous concrete placement.

(2) Segregation. Do not use segregated aggregates until they are thoroughly re-mixed and the resultant pile is of uniform and acceptable grading at any point from which a representative sample is taken.

(3) Cement. Protect cement in storage or stockpiled on the site from any damage by climatic conditions which would change the characteristics or usability of the material.

(4) Moisture. If the moisture content of an approved aggregate remains constant within a tolerance of 0.5 percent plus or minus from the average of that day, they may be used. However, if the moisture content in the aggregate varies by more than the above tolerance, then take whatever corrective measures are necessary to bring the moisture to a constant and uniform quantity before any more concrete is placed. This may be accomplished by handling or manipulating the stockpiles to reduce the moisture content or by adding moisture to the stockpiles in a manner that will produce a uniform moisture content through all portions of the stockpile.

If plant equipment includes an approved accurate moisture-determining device which will make possible the determination of the free moisture in the aggregates and provisions are made for batch to batch correction of the amount of water and the weight of aggregates added, the above requirements relative to handling or manipulating the stockpiles for moisture control will be waived. However, any procedure used will not relieve the producer of the responsibility for delivery of concrete of uniform slump within the limits specified.

Do not use aggregate in the form of frozen lumps in the manufacture of concrete.

(5) Separation of Materials in Tested and Approved Stockpiles. Only use KDOT Approved Materials. Provide separate means for storing materials approved by the Department. If the producer elects to use KDOT Approved Materials for other work for his own convenience, during the progress of a project requiring KDOT Approved Materials, he must so inform the Engineer and agree to pay all costs of having the additional materials tested.

Clean all conveyors, bins and hoppers of unapproved materials before starting to manufacture concrete for the work.

402.5 MIXING, DELIVERY, AND PLACEMENT LIMITATIONS.

a. Concrete Batching, Mixing, and Delivery. Batch and mix the concrete in a central-mix plant, in a truck mixer, or in a drum mixer at the work site. Provide plant capacity and delivery capacity sufficient to insure continuous delivery at the rate required. The rate of delivery of concrete during concreting operations must provide for the proper handling, placing and finishing of the concrete.

The Engineer must approve the concrete plant/batch site before any concrete is produced for the project. The Engineer will inspect and review the equipment, the method of storing and handling of materials, the production procedures, and the transportation and rate of delivery of concrete from the plant to the point of use. The Engineer will grant approval of the concrete plant/batch site based on compliance with the specified requirements. The Engineer may, at any time, rescind permission to use concrete from a previously approved concrete plant/batch site upon failure to comply with the specified requirements.

The mixing drum must be clean before it is charged with the concrete mixture. Charge the batch into the mixing drum so that a portion of the water is in the drum before the aggregates and cement. The flow of water into the drum throughout the batching operation must be uniform, with all of the water in the drum by the end of the first 15 seconds of the mixing cycle. Keep the throat of the drum free of accumulations that restrict the flow of materials into the drum.

Do not exceed the rated capacity (cubic yards (cu m) shown on the manufacturer's plate on the mixer) of the mixer when batching the concrete. However, the Engineer will allow an overload of up to 10 percent above the rated capacity for central-mix plants and drum mixers at the work site, provided the concrete test data for strength, segregation, and uniform consistency are satisfactory, and no concrete is spilled during the mixing cycle.

Operate the mixing drum at the speed specified by the mixer's manufacturer (shown on the manufacturer's plate on the mixer).

Mixing time is measured from the time all materials, except water, are in the drum. If it is necessary to increase the mixing time to obtain the specified percent of air in air-entrained concrete, the Engineer will determine the mixing time.

If the concrete is mixed in a central-mix plant or a drum mixer at the work site, mix the batch at least 60 seconds, but not more than 5 minutes at mixing speed, with the total mixing revolutions not exceeding 60 revolutions. Mixing time begins after all materials, except water, are in the drum, and ends when the discharge chute opens. Transfer time in multiple drum mixers is included in mixing time. Mix time may be reduced for plants utilizing high performance mixing drums provided satisfactory evidence can be provided to the Engineer that thoroughly mixed and uniform concrete is being produced with the proposed mix time. Performance of the plant must conform to the requirements of Table A1.1, of ASTM C 94, Standard Specification for Ready Mixed Concrete. Five of the six tests listed in Table A1.1 must be within the limits of the specification to indicate that uniform concrete is being produced.

If the concrete is mixed in a truck mixer, mix the batch at least 70 revolutions, but not more than 100 revolutions of the drum or blades at mixing speed. After the mixing is completed, set the truck mixer drum at agitating speed. Unless the mixing unit is equipped with an accurate and dependable device that will indicate and control the number of revolutions at mixing speed, perform the mixing at the batch plant and operate the mixing unit at agitating speed while traveling from the plant to the work site. Do not exceed 350 total revolutions (mixing and agitating).

If a truck mixer or truck agitator is used to transport concrete that was completely mixed in a stationary central mixer, agitate the concrete while transporting at the agitating speed specified by the manufacturer of the equipment (shown on the manufacturer's plate on the equipment). Do not exceed 250 total revolutions (additional re-mixing and agitating).

Provide a time slip, for each batch of concrete delivered at the work site, issued at the batching plant that bears the time of charging of the mixer drum with cement and aggregates. On paving projects and other high volume work, the Engineer will determine the haul time and thereafter make random checks, and tickets for every load are not required.

If non-agitating equipment is used for transportation of concrete, provide approved covers for protection against the weather when required by the Engineer.

Place non-agitated concrete within 30 minutes of adding the cement to the water.

TABLE 402-3, Ambient Air Temperature and Agitated Concrete Placement Time

T_{air} = Ambient Air Temperature at Time of Batching °F (°C)	Time limit agitated concrete must be placed within, after the addition of cement to water (hours)	Admixtures
T_{air} < 75 (24)	1 ½	None
75 (24) ≤ T_{air} < 90 (32)	1	None
75 (24) ≤ T_{air} < 90 (32)	1 ½	Set Retarder
90 (32) ≤ T_{air}	1	None

Note: Maximum concrete temperature is 75°F (24ºC).

Do not use concrete that has developed its initial set. Regardless of the speed of delivery and placement, the Engineer will suspend the concreting operations until corrective measures are taken if there is evidence that the concrete can not be adequately consolidated.

Adding water to concrete after the initial mixing is prohibited, with this exception:
If the concrete is delivered to the work site in a truck mixer, the Engineer will allow water (up to 2 gallons per cubic yard (10 L/cu m) be withheld from the mixture at the batch site, and if needed, added at the work site to adjust the slump to comply with the specified requirements. Determine the need for additional water as soon as the load arrives at the construction site. Use a calibrated water-measuring device to add the water, and add the water to the entire load. Do not add more water than was withheld at the batch site. After the additional water is added, turn the drum or blades an additional 20 to 30 revolutions at mixing speed. The Engineer will supervise the adding of water to the load, and will allow this procedure only once per load.

b. Placement Limitations

(1) For Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete, test a field trial batch (one truckload or at least 6 cubic yards (5 cu m)) at least 35 days prior to commencement of placement of the bridge decks. Produce the trial batch from the same plant that will supply the job concrete. Haul time to the jobsite should be simulated prior to discharge of the concrete for testing. Prior to placing concrete in the trial slab and on the job, submit documentation to the Engineer verifying that the trial batch concrete meets the requirements for air content, slump, temperature of plastic concrete, compressive strength, unit weight, and other testing as required by the Engineer.

Before the concrete mixture with plasticizing admixture is used on the project, determine the air content of the trial batch. Monitor the slump, air content, temperature, and workability at initial batching and estimated time of concrete placement. If these properties are not adequate, repeat the trial batch until it can be demonstrated that the mix is within acceptable limits as specified in this document.

(2) Placing Concrete at Night. Do not mix, place or finish concrete without sufficient natural light, unless an adequate and artificial lighting system approved by the Engineer is provided.

(3) Placing Concrete in Cold Weather. Unless authorized otherwise by the Engineer, discontinue mixing and concreting operations when the descending ambient air temperature reaches 40°F (4ºC), and do not resume until an ascending ambient air temperature reaches 35°F (2ºC).

If the Engineer permits placing concrete during cold weather, aggregates may be heated by either steam or dry heat before placing them in the mixer. Use an apparatus that heats the weight uniformly and is so arranged as to preclude the possible occurrence of overheated areas which might injure the materials. Do not heat aggregates directly by gas or oil flame or on sheet metal over fire. Aggregates that are heated in bins, by steam-coil or water-coil heating, or by other methods not detrimental to the aggregates may be used. The use of live steam on or through binned aggregates is not permitted. Unless otherwise authorized, the temperature of the mixed concrete must be at least 50°F (10ºC), but not more than 75°F (24ºC) at the time of placing it in the forms. Do not place concrete when there is a probability of air temperatures being more than 25°F (14°C) below the temperature of the concrete during the first 24 hours after placement unless insulation is provided for both the deck and the girders._Do not, under any circumstances, continue concrete operations if the ambient air temperature is less than 20°F (-7ºC).

If the ambient air temperature is 35°F (2ºC) or less at the time the concrete is placed, the Engineer may require that the water and the aggregates be heated to at least 70°F (21ºC), but not more than 120°F (49ºC).

Do not place concrete on frozen subgrade or use frozen aggregates in the concrete.

(4) Placing Concrete in Hot Weather. When the ambient temperature is above 90^{o}F (32°C), cool the forms, reinforcing steel, steel beam flanges, and other surfaces which will come in contact with the mix to below 90^{o}F (32°C) by means of a water spray or other approved methods. For Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete, cool the concrete mixture to maintain the temperature immediately before placement between 50°F (10ºC) and 75°F (24ºC).

The temperature of the concrete at time of placement shall be maintained within the specified temperature range by any combination of the following:

- Shading the materials storage areas or the production equipment.
- Cooling the aggregates by sprinkling with potable water.
- Cooling the aggregates or water by refrigeration or replacing a portion or all of the mix water with ice that is flaked or crushed to the extent that the ice will completely melt during mixing of the concrete.
- Liquid nitrogen injection.

402.6 INSPECTION AND TESTING.

Obtain samples of fresh concrete for the determination of slump, temperature, weight per cubic yard (meter), and percent of air from the site the concrete is placed.

The Engineer will cast, store, and test strength test specimens in sets of 5. See requirements in **Table 402-4**.

The Department will conduct the sampling and test the samples according to **Section 2500** and **Table 402-4**.

TABLE 402-4, Sampling and Testing Frequency Chart

Tests Required (Record to)	Test Method	CMS	Verification Samples and Tests	Acceptance Samples and Tests
Slump (0.25 in or 5 mm)	KT-21	a	Each of first 3 truckloads for any individual placement, then 1 of every 2 truckloads	
Temperature (1°F or 0.5°C)	KT-17	a	Every truckload	
Mass (0.1 lb or 50 g)	KT-20	a	Every 4 truckloads	
Air Content (0.25%)	KT-18 or KT-19	a	Each of first 3 truckloads for any individual placement, then 1 of every 4 truckloads	
Cylinders (1 lbf or 1 N; 0.1 in or 1 mm; 1 psi or 0.01 MPa)	KT-22 and AASHTO T 22	VER	Make at least five cylinders per pour or major mix design change. Three test cylinders are to be cured according to KT-22 and two test cylinders will be field-cured. Store the field-cured cylinders on or adjacent to the bridge. Protect all surfaces of the cylinders from the elements in as near as possible the same way as the deck concrete. Test the field-cured cylinders at the same age as the standard-cured cylinders.	
Density of Fresh Concrete (0.1 lb/cu ft (1 kg/cu m) or 0.1% of optimum density)	KT-36	ACI		b,c: 1 per 150 cu yd (150 cu m) for thin overlays and bridge deck surfacing.

Note a: "Type Insp" must = "ACC" when the assignment of a pay quantity is being made. "ACI" when recording test values for additional acceptance information.
Note b: Normal operation. Minimum frequency for exceptional conditions may be reduced by the District Materials Engineer on a project basis, written justification shall be made to the Chief of the Bureau of Materials and Research and placed in the project documents. (Multi-Level Frequency Chart (see page 17, Appendix A of Construction Manual, Part V).
Note c: Applicable only when specifications contain those requirements.

The Engineer will reject concrete that does not comply with specified requirements.

The Engineer will permit occasional deviations below the specified cement content, if it is due to the air content of the concrete exceeding the designated air content, but only up to the plus 1.0 percent tolerance in the air content. Continuous operation below the specified cement content for any reason is not permitted.

As the work progresses, the Engineer reserves the right to require the Contractor to change the proportions if conditions warrant such changes to produce a satisfactory mix. Any such changes may be made within the limits of the Specifications at no additional compensation to the Contractor.

08-16-04 M&R (REK)

PCC000078 ACCP	Conc (MA) Grade 3.5 (24) (AE) (LC-HPC)	cu yd	(cu m)	90M-7181
PCC000079 ACCP	Conc (CF) Grade 3.5 (24) (AE) (LC-HPC)	cu yd	(cu m)	90M-7181

7181

KANSAS DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION TO THE
STANDARD SPECIFICATIONS 1990 EDITION

NOTE: This special provision is generally written in the imperative mood. The subject, "the *Contractor*" is implied. Also implied in this language are "*shall*", "*shall be*", or similar words and phrases. The word "*will*" generally pertains to decisions or actions` of the Kansas Department of Transportation.

Section 402. Delete the Section and replace with this:

SECTION 402

LOW CRACKING HIGH PERFORMANCE - CONCRETE

402.1 DESCRIPTION

Provide the grades of concrete specified in the Contract Documents.

402.2 MATERIALS

Provide coarse, fine, and mixed aggregates that comply with the requirements of **Special Provision 90M-7182**.

Provide admixtures that comply with the requirements of **Section 1400**.

Provide cement that complies with the requirements of **Special Provision 90M-7183**.

Provide water for concrete that complies with the requirements of **Section 2400**.

402.3 CONCRETE MIX DESIGN

a. General. The Contractor (or a prospective bidder) may contact the District Materials Engineer or the Bureau of Materials and Research for any available information to help determine approximate proportions which will produce concrete having the required characteristics.

The Contractor is responsible for the actual proportions of the concrete mix. If the Contractor requests (in writing), the Engineer will assist in the design of the concrete mix. A copy of the final design is to be submitted to the District Materials Engineer and Bureau of Materials and Research.

Design the concrete mixes specified in the Contract Documents. Design concrete mixes that comply with these requirements:

b. Air-Entrained Concrete for Bridge Decks. Design air-entrained concrete for structures according to these requirements:

TABLE 402-1, Air-Entrained Concrete for Bridge Decks

Grade of Concrete Type of Aggregate (Section 1100)	lb. (kg) of Cement per cu yd (cu m) of Concrete, min/max	lb (kg) of Water per lb (kg) of Cement, max*	Designated Air Content Percent by Volume**
Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC))			
MA-4	522 (310)/ 563(334)	0.45	8.0 ± 1.0

*Maximum limit of lb. (kg) of water per lb. (kg) of cement includes free water in aggregates, but excludes water of absorption of the aggregates.
** Concrete with an air content less than 6.5% or greater than 9.5% shall be rejected.
NOTE: For Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete, the total volume of water and cement shall not exceed 27% of the mix.

c. Portland Cement. Select the type of portland cement specified in the Contract Documents. No mineral admixtures are permitted for Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete.

d. Design Air Content. Use the middle of the specified air content range for the design of air-entrained concrete.

e. Admixtures for Acceleration, Air-Entraining, Plasticizing, Set Retardation, and Water Reduction. Use the dosages recommended by the admixture manufacturers. Incorporate and mix the admixtures into the concrete mixtures according to the manufacturer's recommendations.

Determine the quantity of each admixture for the concrete mix design.

If another admixture is added to an air-entrained concrete mixture, determine if it is necessary to adjust the air-entraining admixture dosage to maintain the specified air content.

Admixtures containing chloride ion (CL) in excess of 0.1 percent by mass of the admixture shall not be used in Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete.

(1) Accelerating Admixture. If specified in the Contract Documents, or in situations that involve contact with reinforcing steel and require early strength development to expedite opening to traffic, a non-chloride accelerator may be appropriate. The Engineer may approve the use of a Type C or E accelerating admixture.

(2) Air-Entraining Admixture. If specified, use air-entraining admixture in the concrete mixture.

If the concrete mixture also contains a plasticizing or a water reducing, high range admixture, use only a vinsol resin or tall oil based air-entraining admixture.

(3) Plasticizing Admixture. Include a batching sequence in the concrete mix design. Consider the location of the concrete plant in relation to the job site, and identify the approximate quantity, when and at what location the plasticizing admixture is added to the concrete mixture. Do not add water after the plasticizing admixture is added to the concrete mixture.

Manufacturers of plasticizing admixtures may recommend mixing revolutions beyond the limits specified in **subsection 402.5**. If necessary, address the additional mixing revolutions (the Engineer will allow up to 60 additional revolutions) in the concrete mix design.

Accomplish slump control in the field by redosing. If time and temperature limits are not exceeded, and if at least 30 mixing revolutions remain, the Engineer will allow redosing with up to 50 percent of the original dose.

(4) Water Reduction and Set Retardation. If unfavorable weather or other conditions adversely affect the placing and finishing properties of the concrete mix, the Engineer may allow the use of water reducing and set retarding admixtures. If the Engineer approves the use of water reducing and set retarding admixtures, their continued use depends on their performance. It is the Contractor's responsibility to insure that the admixtures will work as intended without detrimental effects.

(5) Adjust the mix designs during the course of the work when necessary to ensure compliance with the specified fresh and hardened concrete properties. Only permit such modifications after trial batches to demonstrate that the adjusted mix design will result in concrete that complies with the specified concrete properties.

The Engineer will allow adjustments to the dose rate of air entraining, water-reducing and retarding chemical admixtures to compensate for environmental changes during placement without a new concrete mix design or trial batch.

f. Designated Slump. Designate a slump for each concrete mix design that is within these limits:

TABLE 402-2, Designated Slump

Type of Work:	Designated Slump in. (mm)	Maximum Allowable Slump in. (mm)
Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC))	1 ½ - 3 (36-75)	4 (100)

NOTE: When high range water reducing admixtures are used with Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete mixtures, **Table 402-2** slump limits shall not be exceeded.

g. Approval of Concrete Mix Designs. Submit all concrete mix designs to the Engineer and the Research Development Engineer for review and approval. Submit completed volumetric mix designs on KDOT Form No. 694 (or other forms approved by the District Materials Engineer).

Do not place any concrete on the Project until the Engineer approves the concrete mix designs, trial batch, and trial slab. Once the Engineer approves the concrete mix design, do not make changes without the Engineer's approval (see Section 402.5b).

402.4 REQUIREMENTS FOR COMBINED MATERIALS.

a. Measurements for Proportioning Materials.

(1) Cement. Measure cement as packed by the manufacturer. A sack of cement is considered as 0.04 cubic yards (0.03 cu m) weighing 94 pounds (42.6 kg) net. Measure bulk cement by weight. In either case, the measurement must be accurate to within 0.5 percent throughout the range of use.

(2) Water. Measure the mixing water by weight or by volume. In either case the measurement must be accurate to within 1 percent throughout the range of use.

(3) Aggregates. Measure the aggregates by weight. The measurement must be accurate to within 0.5 percent throughout the range of use.

(4) Admixtures. Measure liquid admixtures by weight or volume. If liquid admixtures are used in small quantities in proportion to the cement as in the case of air-entraining agents, use readily adjustable mechanical dispensing equipment capable of being set to deliver the required quantity and to cut off the flow automatically when this quantity is discharged. The measurement must be accurate to within 3 percent of the quantity required.

b. Testing of Aggregates. Testing Aggregates at the Batch Site. Provide the Engineer with reasonable facilities at the batch site for obtaining samples of the aggregates. Provide adequate and safe laboratory facilities at the batch site that will allow the Engineer to test the aggregates for compliance with the specified requirements.

The Department will sample and test aggregates from each source to determine their compliance with specifications. Batching of the concrete mixture is not permitted until the Engineer has determined that the aggregates comply with the specifications. The Department will conduct the sampling at the batching site, and test the samples according to the Frequency Testing Chart in Part V of the KDOT Construction Manual. For QC/QA Contracts, the Contractor will determine testing intervals within the specified minimum frequency.

After initial testing is complete and the Engineer has determined that the aggregate process control is satisfactory, use the aggregates concurrently with sampling and testing as long as tests indicate compliance with specifications. During the batching operations, sample the aggregates as near the point of batching as feasible. Sample from the stream as the storage bins or weigh hoppers are loaded. If samples cannot be reasonably taken from the stream, take them from approved stockpiles. If test results indicate that an aggregate does not comply with specifications, cease concrete production using that aggregate. Unless a tested and approved stockpile for that aggregate is available at the batch plant, do not use any additional aggregate from that source and specified grading until subsequent sampling and testing of that aggregate indicate compliance with specifications. When tests are completed and the Engineer is satisfied that process control is again adequate, production of concrete using aggregates sampled and tested concurrently with production may resume.

c. Handling of Materials.

(1) Approved stockpiles are permitted only at the batch plant and only for small concrete placements or for the purpose of maintaining concrete production. Mark the approved stockpile with an “Approved Materials” sign. Provide a suitable stockpile area at the batch plant so that aggregates are stored without detrimental segregation or contamination. Unless otherwise approved by the Engineer, no more than 250 tons (Mg) of coarse aggregate and no more than 250 tons (Mg) of fine aggregate tested and approved by the Engineer may be stockpiled at the plant. If mixed aggregate is used, limit the approved stockpile to 500 tons (Mg), the size of each being proportional to the amount of each aggregate to be used in the mix.

Load aggregates into the mixer in such a manner that no material foreign to the concrete or material capable of changing the desired proportions is included. In the event 2 or more sizes or types of coarse or fine aggregates are used on the same project, only 1 size or type of each aggregate may be used on 1 continuous concrete placement.

(2) Segregation. Do not use segregated aggregates until they are thoroughly re-mixed and the resultant pile is of uniform and acceptable grading at any point from which a representative sample is taken.

(3) Cement. Protect cement in storage or stockpiled on the site from any damage by climatic conditions which would change the characteristics or usability of the material.

(4) Moisture. If the moisture content of an approved aggregate remains constant within a tolerance of 0.5 percent plus or minus from the average of that day, they may be used. However, if the moisture content in the aggregate varies by more than the above tolerance, then take whatever corrective measures are necessary to bring the moisture to a constant and uniform quantity before any more concrete is placed. This may be accomplished by handling or manipulating the stockpiles to reduce the moisture content or by adding moisture to the stockpiles in a manner that will produce a uniform moisture content through all portions of the stockpile.

If plant equipment includes an approved accurate moisture-determining device which will make possible the determination of the free moisture in the aggregates and provisions are made for batch to batch correction of the amount of water and the weight of aggregates added, the above requirements relative to handling or manipulating the stockpiles for moisture control will be waived. However, any procedure used will not relieve the producer of the responsibility for delivery of concrete of uniform slump within the limits specified.

Do not use aggregate in the form of frozen lumps in the manufacture of concrete.

(5) Separation of Materials in Tested and Approved Stockpiles. Only use KDOT Approved Materials. Provide separate means for storing materials approved by the Department. If the producer elects to use KDOT Approved Materials for other work for his own convenience, during the progress of a project requiring KDOT Approved Materials, he must so inform the Engineer and agree to pay all costs of having the additional materials tested.

Clean all conveyors, bins and hoppers of unapproved materials before starting to manufacture concrete for the work.

402.5 MIXING, DELIVERY, AND PLACEMENT LIMITATIONS.

a. Concrete Batching, Mixing, and Delivery. Batch and mix the concrete in a central-mix plant, in a truck mixer, or in a drum mixer at the work site. Provide plant capacity and delivery capacity sufficient to insure continuous delivery at the rate required. The rate of delivery of concrete during concreting operations must provide for the proper handling, placing and finishing of the concrete.

The Engineer must approve the concrete plant/batch site before any concrete is produced for the project. The Engineer will inspect and review the equipment, the method of storing and handling of materials, the production procedures, and the transportation and rate of delivery of concrete from the plant to the point of use. The Engineer will grant approval of the concrete plant/batch site based on compliance with the specified requirements. The Engineer may, at any time, rescind permission to use concrete from a previously approved concrete plant/batch site upon failure to comply with the specified requirements.

The mixing drum must be clean before it is charged with the concrete mixture. Charge the batch into the mixing drum so that a portion of the water is in the drum before the aggregates and cement. The flow of water into the drum throughout the batching operation must be uniform, with all of the water in the drum by the end of the first 15 seconds of the mixing cycle. Keep the throat of the drum free of accumulations that restrict the flow of materials into the drum.

Do not exceed the rated capacity (cubic yards (cu m) shown on the manufacturer's plate on the mixer) of the mixer when batching the concrete. However, the Engineer will allow an overload of up to 10 percent above the rated capacity for central-mix plants and drum mixers at the work site, provided the concrete test data for strength, segregation, and uniform consistency are satisfactory, and no concrete is spilled during the mixing cycle.

Operate the mixing drum at the speed specified by the mixer's manufacturer (shown on the manufacturer's plate on the mixer).

Mixing time is measured from the time all materials, except water, are in the drum. If it is necessary to increase the mixing time to obtain the specified percent of air in air-entrained concrete, the Engineer will determine the mixing time.

If the concrete is mixed in a central-mix plant or a drum mixer at the work site, mix the batch at least 60 seconds, but not more than 5 minutes at mixing speed, with the total mixing revolutions not exceeding 60 revolutions. Mixing time begins after all materials, except water, are in the drum, and ends when the discharge chute opens. Transfer time in multiple drum mixers is included in mixing time. Mix time may be reduced for plants utilizing high performance mixing drums provided satisfactory evidence can be provided to the Engineer that thoroughly mixed and uniform concrete is being produced with the proposed mix time. Performance of the plant must conform to the requirements of Table A1.1, of ASTM C 94, Standard Specification for Ready Mixed Concrete. Five of the six tests listed in Table A1.1 must be within the limits of the specification to indicate that uniform concrete is being produced.

If the concrete is mixed in a truck mixer, mix the batch at least 70 revolutions, but not more than 100 revolutions of the drum or blades at mixing speed. After the mixing is completed, set the truck mixer drum at agitating speed. Unless the mixing unit is equipped with an accurate and dependable device that will indicate and control the number of revolutions at mixing speed, perform the mixing at the batch plant and operate the mixing unit at agitating speed while traveling from the plant to the work site. Do not exceed 350 total revolutions (mixing and agitating).

If a truck mixer or truck agitator is used to transport concrete that was completely mixed in a stationary central mixer, agitate the concrete while transporting at the agitating speed specified by the manufacturer of the equipment (shown on the manufacturer's plate on the equipment). Do not exceed 250 total revolutions (additional re-mixing and agitating).

Provide a time slip, for each batch of concrete delivered at the work site, issued at the batching plant that bears the time of charging of the mixer drum with cement and aggregates. On paving projects and other high volume work, the Engineer will determine the haul time and thereafter make random checks, and tickets for every load are not required.

If non-agitating equipment is used for transportation of concrete, provide approved covers for protection against the weather when required by the Engineer.

Place non-agitated concrete within 30 minutes of adding the cement to the water.

TABLE 402-3, Ambient Air Temperature and Agitated Concrete Placement Time

T_{air} = Ambient Air Temperature at Time of Batching °F (°C)	**Time limit agitated concrete must be placed within, after the addition of cement to water (hours)**	**Admixtures**
T_{air} < 75 (24)	1 ½	None
75 (24) ≤ T_{air} < 90 (32)	1	None
75 (24) ≤ T_{air} < 90 (32)	1 ½	Set Retarder
90 (32) ≤ T_{air}	1	None

Note: Maximum concrete temperature is 70°F (21ºC) [75°F (24ºC) with approval of the engineer].

Do not use concrete that has developed its initial set. Regardless of the speed of delivery and placement, the Engineer will suspend the concreting operations until corrective measures are taken if there is evidence that the concrete can not be adequately consolidated.

Adding water to concrete after the initial mixing is prohibited, with this exception:
If the concrete is delivered to the work site in a truck mixer, the Engineer will allow water (up to 2 gallons per cubic yard (10 L/cu m) be withheld from the mixture at the batch site, and if needed, added at the work site to adjust the slump to comply with the specified requirements. Determine the need for additional water as soon as the load arrives at the construction site. Use a calibrated water-measuring device to add the water, and add the water to the entire load. Do not add more water than was withheld at the batch site. After the additional water is added, turn the drum or blades an additional 20 to 30 revolutions at mixing speed. The Engineer will supervise the adding of water to the load, and will allow this procedure only once per load.

b. Placement Limitations

(1) For Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete, test a field trial batch (one truckload or at least 6 cubic yards (5 cu m)) at least 35 days prior to commencement of placement of the bridge decks. Produce the trial batch from the same plant that will supply the job concrete. Haul time to the jobsite should be simulated prior to discharge of the concrete for testing. Prior to placing concrete in the trial slab and on the job, submit documentation to the Engineer verifying that the trial batch concrete meets the requirements for air content, slump, temperature of plastic concrete, compressive strength, unit weight, and other testing as required by the Engineer.

Before the concrete mixture with plasticizing admixture is used on the project, determine the air content of the trial batch. Monitor the slump, air content, temperature, and workability at initial batching and estimated time of concrete placement. If these properties are not adequate, repeat the trial batch until it can be demonstrated that the mix is within acceptable limits as specified in this document.

(2) Placing Concrete at Night. Do not mix, place or finish concrete without sufficient natural light, unless an adequate and artificial lighting system approved by the Engineer is provided.

(3) Placing Concrete in Cold Weather. Unless authorized otherwise by the Engineer, discontinue mixing and concreting operations when the descending ambient air temperature reaches 40°F (4ºC), and do not resume until an ascending ambient air temperature reaches 35°F (2ºC).

If the Engineer permits placing concrete during cold weather, aggregates may be heated by either steam or dry heat before placing them in the mixer. Use an apparatus that heats the weight uniformly and is so arranged as to preclude the possible occurrence of overheated areas which might injure the materials. Do not heat aggregates directly by gas or oil flame or on sheet metal over fire. Aggregates that are heated in bins, by steam-coil or water-coil heating, or by other methods not detrimental to the aggregates may be used. The use of live steam on or through

binned aggregates is not permitted. Unless otherwise authorized, the temperature of the mixed concrete must be at least 55°F (13ºC), but not more than 70°F (21ºC) at the time of placing it in the forms. With approval by the engineer, the temperature of the concrete may be up to 5°F (3ºC) below or above this range. Do not place concrete when there is a probability of air temperatures being more than 25°F (14°C) below the temperature of the concrete during the first 24 hours after placement unless insulation is provided for both the deck and the girders. Do not, under any circumstances, continue concrete operations if the ambient air temperature is less than 20°F
(-7ºC).

If the ambient air temperature is 35°F (2ºC) or less at the time the concrete is placed, the Engineer may require that the water and the aggregates be heated to at least 70°F (21ºC), but not more than 120°F (49ºC).

Do not place concrete on frozen subgrade or use frozen aggregates in the concrete.

(4) Placing Concrete in Hot Weather. When the ambient temperature is above 90°F (32°C), cool the forms, reinforcing steel, steel beam flanges, and other surfaces which will come in contact with the mix to below 90°F (32°C) by means of a water spray or other approved methods. For Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete, cool the concrete mixture to maintain the temperature immediately before placement between 55°F (13ºC) and 70°F (21ºC). With approval by the engineer, the temperature of the concrete may be up to 5°F (3ºC) below or above this range.

The temperature of the concrete at time of placement shall be maintained within the specified temperature range by any combination of the following:

- Shading the materials storage areas or the production equipment.
- Cooling the aggregates by sprinkling with potable water.
- Cooling the aggregates or water by refrigeration or replacing a portion or all of the mix water with ice that is flaked or crushed to the extent that the ice will completely melt during mixing of the concrete.
- Liquid nitrogen injection.

402.6 INSPECTION AND TESTING.

Obtain samples of fresh concrete for the determination of slump, temperature, weight per cubic yard (meter), and percent of air from the site the concrete is placed.

The Engineer will cast, store, and test strength test specimens in sets of 5. See requirements in **Table 402-4**.

The Department will conduct the sampling and test the samples according to **Section 2500** and **Table 402-4**.

TABLE 402-4, Sampling and Testing Frequency Chart

Tests Required (Record to)	Test Method	CMS	Verification Samples and Tests	Acceptance Samples and Tests
Slump (0.25 in or 5 mm)	KT-21	a	Each of first 3 truckloads for any individual placement, then 1 of every 2 truckloads	
Temperature (1°F or 0.5°C)	KT-17	a	Every truckload	
Mass (0.1 lb or 50 g)	KT-20	a	Every 4 truckloads	
Air Content (0.25%)	KT-18 or KT-19	a	Each of first 3 truckloads for any individual placement, then 1 of every 4 truckloads	
Cylinders (1 lbf or 1 N; 0.1 in or 1 mm; 1 psi or 0.01 MPa)	KT-22 and AASHTO T 22	VER	Make at least five cylinders per pour or major mix design change. Three test cylinders are to be cured according to KT-22 and two test cylinders will be field-cured. Store the field-cured cylinders on or adjacent to the bridge. Protect all surfaces of the cylinders from the elements in as near as possible the same way as the deck concrete. Test the field-cured cylinders at the same age as the standard-cured cylinders.	
Density of Fresh Concrete (0.1 lb/cu ft (1 kg/cu m) or 0.1% of optimum density)	KT-36	ACI		b,c: 1 per 150 cu yd (150 cu m) for thin overlays and bridge deck surfacing.

Note a: "Type Insp" must = "ACC" when the assignment of a pay quantity is being made. "ACI" when recording test values for additional acceptance information.
Note b: Normal operation. Minimum frequency for exceptional conditions may be reduced by the District Materials Engineer on a project basis, written justification shall be made to the Chief of the Bureau of Materials and Research and placed in the project documents. (Multi-Level Frequency Chart (see page 17, Appendix A of Construction Manual, Part V).
Note c: Applicable only when specifications contain those requirements.

The Engineer will reject concrete that does not comply with specified requirements.

The Engineer will permit occasional deviations below the specified cement content, if it is due to the air content of the concrete exceeding the designated air content, but only up to the plus 1.0 percent tolerance in the air content. Continuous operation below the specified cement content for any reason is not permitted.

As the work progresses, the Engineer reserves the right to require the Contractor to change the proportions if conditions warrant such changes to produce a satisfactory mix. Any such changes may be made within the limits of the Specifications at no additional compensation to the Contractor.

08-04-05 M&R (REK)

PCC000078	Conc (MA) Grade 3.5 (24) (AE) (LC-HPC)	cu yd	(cu m)	90M-7181
ACCP				
PCC000079	Conc (CF) Grade 3.5 (24) (AE) (LC-HPC)	cu yd	(cu m)	90M-7181
ACCP				

7275

KANSAS DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION TO THE
STANDARD SPECIFICATIONS 1990 EDITION

NOTE: This special provision is generally written in the imperative mood. The subject, "the *Contractor*" is implied. Also implied in this language are "*shall*", "*shall be*", or similar words and phrases. The word "*will*" generally pertains to decisions or actions` of the Kansas Department of Transportation.

Section 402. Delete the Section and replace with this:

SECTION 402

LOW CRACKING HIGH PERFORMANCE - CONCRETE

402.1 DESCRIPTION

Provide the grades of concrete specified in the Contract Documents.

402.2 MATERIALS

Coarse, fine, and mixed aggregates ....**Special Provision 90M-7326**
Admixtures ....**Section 1400**
Cement ....**Special Provision 90M-7183**
Water...**Section 2400**

402.3 CONCRETE MIX DESIGN

a. General. The Contractor (or a prospective bidder) may contact the District Materials Engineer or the Bureau of Materials and Research for any available information to help determine approximate proportions which will produce concrete having the required characteristics.

The Contractor is responsible for the actual proportions of the concrete mix. If the Contractor requests (in writing), the Engineer will assist in the design of the concrete mix. A copy of the final design is to be submitted to the District Materials Engineer and Bureau of Materials and Research.

Design the concrete mixes specified in the Contract Documents. Design concrete mixes that comply with these requirements:

b. Air-Entrained Concrete for Bridge Decks. Design air-entrained concrete for structures according to these requirements:

TABLE 402-1, Air-Entrained Concrete for Bridge Decks

Grade of Concrete Type of Aggregate (Section 1100)	lb. (kg) of Cement per cu yd (cu m) of Concrete, min/max	lb (kg) of Water per lb (kg) of Cement, max*	Designated Air Content Percent by Volume**
Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC))			
MA-4	500 (300)/ 535(317)	0.42	8.0 ± 1.0

*Maximum limit of lb. (kg) of water per lb. (kg) of cement includes free water in aggregates, but excludes water of absorption of the aggregates.
** Concrete with an air content less than 6.5% or greater than 9.5% shall be rejected.

c. Portland Cement. Select the type of portland cement specified in the Contract Documents. No mineral admixtures are permitted for Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete.

d. Design Air Content. Use the middle of the specified air content range for the design of air-entrained concrete.

e. Admixtures for Acceleration, Air-Entraining, Plasticizing, Set Retardation, and Water Reduction. Use the dosages recommended by the admixture manufacturers. Incorporate and mix the admixtures into the concrete mixtures according to the manufacturer's recommendations.

Determine the quantity of each admixture for the concrete mix design.

If another admixture is added to an air-entrained concrete mixture, determine if it is necessary to adjust the air-entraining admixture dosage to maintain the specified air content.

Admixtures containing chloride ion (CL) in excess of 0.1 percent by mass of the admixture shall not be used in Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete.

(1) Accelerating Admixture. If specified in the Contract Documents, or in situations that involve contact with reinforcing steel and require early strength development to expedite opening to traffic, a non-chloride accelerator may be appropriate. The Engineer may approve the use of a Type C or E accelerating admixture.

(2) Air-Entraining Admixture. If specified, use air-entraining admixture in the concrete mixture.

If the concrete mixture also contains a plasticizing or a water reducing, high range admixture, use only a vinsol resin or tall oil based air-entraining admixture.

(3) Plasticizing Admixture. Include a batching sequence in the concrete mix design. Consider the location of the concrete plant in relation to the job site, and

identify the approximate quantity, when and at what location the plasticizing admixture is added to the concrete mixture. Do not add water after the plasticizing admixture is added to the concrete mixture.

Manufacturers of plasticizing admixtures may recommend mixing revolutions beyond the limits specified in **subsection 402.5**. If necessary, address the additional mixing revolutions (the Engineer will allow up to 60 additional revolutions) in the concrete mix design.

Accomplish slump control in the field by redosing. If time and temperature limits are not exceeded, and if at least 30 mixing revolutions remain, the Engineer will allow redosing with up to 50 percent of the original dose. See also subsection 402.5a.

(4) Water Reduction and Set Retardation. If unfavorable weather or other conditions adversely affect the placing and finishing properties of the concrete mix, the Engineer may allow the use of water reducing and set retarding admixtures. If the Engineer approves the use of water reducing and set retarding admixtures, their continued use depends on their performance. It is the Contractor's responsibility to insure that the admixtures will work as intended without detrimental effects.

(5) Adjust the mix designs during the course of the work when necessary to ensure compliance with the specified fresh and hardened concrete properties. Only permit such modifications after trial batches to demonstrate that the adjusted mix design will result in concrete that complies with the specified concrete properties.

The Engineer will allow adjustments to the dose rate of air entraining, water-reducing and retarding chemical admixtures to compensate for environmental changes during placement without a new concrete mix design or qualification batch.

f. Designated Slump. Designate a slump for each concrete mix design that is within these limits:

TABLE 402-2, Designated Slump

Type of Work:	Designated Slump in. (mm)	Maximum Allowable Slump in. (mm)
Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC))	1 ½ - 3 (36-75)	4 (100)

NOTE: When high range water reducing admixtures are used with Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete mixtures, **Table 402-2** slump limits shall not be exceeded.

g. Approval of Concrete Mix Designs. Submit all concrete mix designs to the Engineer and the Research Development Engineer for review and approval. Submit completed volumetric mix designs on KDOT Form No. 694 (or other forms approved by the District Materials Engineer).

Do not place any concrete on the Project until the Engineer approves the concrete mix designs, qualification batch, and qualification slab. Once the Engineer approves the concrete mix design, do not make changes without the Engineer's approval (see Section 402.5b).

402.4 REQUIREMENTS FOR COMBINED MATERIALS.

a. Measurements for Proportioning Materials.

(1) Cement. Measure cement as packed by the manufacturer. A sack of cement is considered as 0.04 cubic yards (0.03 cu m) weighing 94 pounds (42.6 kg) net. Measure bulk cement by weight. In either case, the measurement must be accurate to within 0.5 percent throughout the range of use.

(2) Water. Measure the mixing water by weight or by volume. In either case the measurement must be accurate to within 1 percent throughout the range of use.

(3) Aggregates. Measure the aggregates by weight. The measurement must be accurate to within 0.5 percent throughout the range of use.

(4) Admixtures. Measure liquid admixtures by weight or volume. If liquid admixtures are used in small quantities in proportion to the cement as in the case of air-entraining agents, use readily adjustable mechanical dispensing equipment capable of being set to deliver the required quantity and to cut off the flow automatically when this quantity is discharged. The measurement must be accurate to within 3 percent of the quantity required.

b. Testing of Aggregates. Testing Aggregates at the Batch Site. Provide the Engineer with reasonable facilities at the batch site for obtaining samples of the aggregates. Provide adequate and safe laboratory facilities at the batch site that will allow the Engineer to test the aggregates for compliance with the specified requirements.

The Department will sample and test aggregates from each source to determine their compliance with specifications. Batching of the concrete mixture is not permitted until the Engineer has determined that the aggregates comply with the specifications. The Department will conduct the sampling at the batching site, and test the samples according to the Frequency Testing Chart in Part V of the KDOT Construction Manual. For QC/QA Contracts, the Contractor will determine testing intervals within the specified minimum frequency.

After initial testing is complete and the Engineer has determined that the aggregate process control is satisfactory, use the aggregates concurrently with sampling and testing as long as tests indicate compliance with specifications. During the batching operations, sample the aggregates as near the point of batching as feasible. Sample from the stream as the storage bins or weigh hoppers are loaded. If samples cannot be reasonably taken from the stream, take them from approved stockpiles. If test results indicate that an aggregate does not comply with specifications, cease concrete production using that aggregate. Unless a tested and approved stockpile for that aggregate is available at the batch plant, do not use any additional aggregate from that source and specified grading until subsequent sampling and testing of that aggregate indicate compliance with specifications. When tests are completed and the Engineer is satisfied that process control is again adequate, production of concrete using aggregates sampled and tested concurrently with production may resume.

c. Handling of Materials.

(1) Approved stockpiles are permitted only at the batch plant and only for small concrete placements or for the purpose of maintaining concrete production. Mark the approved stockpile with an "Approved Materials" sign. Provide a suitable stockpile area at the batch plant so that aggregates are stored without detrimental segregation or contamination. Unless otherwise approved by the Engineer, no more than 250 tons (Mg) of coarse aggregate and no more than 250 tons (Mg) of fine aggregate tested and approved by the Engineer may be stockpiled at the plant. If mixed aggregate is used, limit the approved stockpile to 500 tons (Mg), the size of each being proportional to the amount of each aggregate to be used in the mix.

Load aggregates into the mixer in such a manner that no material foreign to the concrete or material capable of changing the desired proportions is included. In the event 2 or more sizes or types of coarse or fine aggregates are used on the same project, only 1 size or type of each aggregate may be used on 1 continuous concrete placement.

(2) Segregation. Do not use segregated aggregates until they are thoroughly re-mixed and the resultant pile is of uniform and acceptable grading at any point from which a representative sample is taken.

(3) Cement. Protect cement in storage or stockpiled on the site from any damage by climatic conditions which would change the characteristics or usability of the material.

(4) Moisture. If the moisture content of an approved aggregate remains constant within a tolerance of 0.5 percent plus or minus from the average of that day, they may be used. However, if the moisture content in the aggregate varies by more than the above tolerance, then take whatever corrective measures are necessary to bring the moisture to a constant and uniform quantity before any more concrete is placed. This may be accomplished by handling or manipulating the stockpiles to reduce the moisture content or by adding moisture to the stockpiles in a manner that will produce a uniform moisture content through all portions of the stockpile.

If plant equipment includes an approved accurate moisture-determining device which will make possible the determination of the free moisture in the aggregates and provisions are made for batch to batch correction of the amount of water and the weight of aggregates added, the above requirements relative to handling or manipulating the stockpiles for moisture control will be waived. However, any procedure used will not relieve the producer of the responsibility for delivery of concrete of uniform slump within the limits specified.

Do not use aggregate in the form of frozen lumps in the manufacture of concrete.

(5) Separation of Materials in Tested and Approved Stockpiles. Only use KDOT Approved Materials. Provide separate means for storing materials approved

by the Department. If the producer elects to use KDOT Approved Materials for other work for his own convenience, during the progress of a project requiring KDOT Approved Materials, he must so inform the Engineer and agree to pay all costs of having the additional materials tested.

Clean all conveyors, bins and hoppers of unapproved materials before starting to manufacture concrete for the work.

402.5 MIXING, DELIVERY, AND PLACEMENT LIMITATIONS.

a. Concrete Batching, Mixing, and Delivery. Batch and mix the concrete in a central-mix plant, in a truck mixer, or in a drum mixer at the work site. Provide plant capacity and delivery capacity sufficient to insure continuous delivery at the rate required. The rate of delivery of concrete during concreting operations must provide for the proper handling, placing and finishing of the concrete.

The Engineer must approve the concrete plant/batch site before any concrete is produced for the project. The Engineer will inspect and review the equipment, the method of storing and handling of materials, the production procedures, and the transportation and rate of delivery of concrete from the plant to the point of use. The Engineer will grant approval of the concrete plant/batch site based on compliance with the specified requirements. The Engineer may, at any time, rescind permission to use concrete from a previously approved concrete plant/batch site upon failure to comply with the specified requirements.

The mixing drum must be clean before it is charged with the concrete mixture. Charge the batch into the mixing drum so that a portion of the water is in the drum before the aggregates and cement. The flow of water into the drum throughout the batching operation must be uniform, with all of the water in the drum by the end of the first 15 seconds of the mixing cycle. Keep the throat of the drum free of accumulations that restrict the flow of materials into the drum.

Do not exceed the rated capacity (cubic yards (cu m) shown on the manufacturer's plate on the mixer) of the mixer when batching the concrete. However, the Engineer will allow an overload of up to 10 percent above the rated capacity for central-mix plants and drum mixers at the work site, provided the concrete test data for strength, segregation, and uniform consistency are satisfactory, and no concrete is spilled during the mixing cycle.

Operate the mixing drum at the speed specified by the mixer's manufacturer (shown on the manufacturer's plate on the mixer).

Mixing time is measured from the time all materials, except water, are in the drum. If it is necessary to increase the mixing time to obtain the specified percent of air in air-entrained concrete, the Engineer will determine the mixing time.

If the concrete is mixed in a central-mix plant or a drum mixer at the work site, mix the batch at least 60 seconds, but not more than 5 minutes at mixing speed, with the total mixing revolutions not exceeding 60 revolutions. Mixing time begins after all materials, except water, are in the drum, and ends when the discharge chute opens. Transfer time in multiple drum mixers is included in mixing time. Mix time may be reduced for plants utilizing high performance mixing drums provided satisfactory evidence can be provided to the Engineer that thoroughly mixed and uniform concrete is being produced with the proposed mix time. Performance of the plant must conform to the requirements of Table A1.1, of ASTM C 94, Standard Specification for Ready Mixed Concrete. Five of the six tests listed in Table A1.1 must be within the limits of the specification to indicate that uniform concrete is being produced.

If the concrete is mixed in a truck mixer, mix the batch at least 70 revolutions, but not more than 100 revolutions of the drum or blades at mixing speed. After the mixing is completed, set the truck mixer drum at agitating speed. Unless the mixing unit is equipped with an accurate and dependable device that will indicate and control the number of revolutions at mixing speed, perform the mixing at the batch plant and operate the mixing unit at agitating speed while traveling from the plant to the work site. Do not exceed 350 total revolutions (mixing and agitating).

If a truck mixer or truck agitator is used to transport concrete that was completely mixed in a stationary central mixer, agitate the concrete while transporting at the agitating speed specified by the manufacturer of the equipment (shown on the manufacturer's plate on the equipment). Do not exceed 250 total revolutions (additional re-mixing and agitating).

Provide a time slip, for each batch of concrete delivered at the work site, issued at the batching plant that bears the time of charging of the mixer drum with cement and aggregates. On paving projects and other high volume work, the Engineer will determine the haul time and thereafter make random checks, and tickets for every load are not required.

If non-agitating equipment is used for transportation of concrete, provide approved covers for protection against the weather when required by the Engineer.

Place non-agitated concrete within 30 minutes of adding the cement to the water.

TABLE 402-3, Ambient Air Temperature and Agitated Concrete Placement Time

T_{air} = Ambient Air Temperature at Time of Batching °F (°C)	Time limit agitated concrete must be placed within, after the addition of cement to water (hours)	Admixtures
T_{air} < 75 (24)	1 ½	None
75 (24) ≤ T_{air} < 90 (32)	1	None
75 (24) ≤ T_{air} < 90 (32)	1 ½	Set Retarder
90 (32) ≤ T_{air}	1	None

Note: Maximum concrete temperature is 70°F (21°C) [75°F (24°C) with approval of the engineer].

Do not use concrete that has developed its initial set. Regardless of the speed of delivery and placement, the Engineer will suspend the concreting operations until corrective measures are taken if there is evidence that the concrete can not be adequately consolidated.

Adding water to concrete after the initial mixing is prohibited, with this exception:
If the concrete is delivered to the work site in a truck mixer, the Engineer will allow water [up to 2 gallons per cubic yard (10 L/cu m) (16 pounds per cubic yard) (9.6 kg/cu m)] be withheld from the mixture at the batch site, and if needed, added at the work site to adjust the slump to comply with the specified requirements. Determine the need for additional water as soon as the load arrives at the construction site. Use a calibrated water-measuring device to add the water, and add the water to the entire load. Do not add more water than was withheld at the batch site. After the additional water is added, turn the drum or blades an additional 20 to 30 revolutions at mixing speed. The Engineer will supervise the adding of water to the load, and will allow this procedure only once per load. See also subsection 402.3e(3).

b. Placement Limitations

(1) For Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete, qualify a field batch (one truckload or at least 6 cubic yards (5 cu m)) at least 35 days prior to commencement of placement of the bridge decks. Produce the qualification batch from the same plant that will supply the job concrete. Haul time to the jobsite should be simulated prior to discharge of the concrete for testing. Prior to placing concrete in the qualification slab and on the job, submit documentation to the Engineer verifying that the qualification batch concrete meets the requirements for air content, slump, temperature of plastic concrete, compressive strength, unit weight, and other testing as required by the Engineer.

Before the concrete mixture with plasticizing admixture is used on the project, determine the air content of the qualification batch. Monitor the slump, air content, temperature, and workability at initial batching and estimated time of concrete placement. If these properties are not adequate, repeat the qualification batch until it can be demonstrated that the mix is within acceptable limits as specified in this document.

(2) Placing Concrete at Night. Do not mix, place or finish concrete without sufficient natural light, unless an adequate and artificial lighting system approved by the Engineer is provided.

(3) Placing Concrete in Cold Weather. Unless authorized otherwise by the Engineer, discontinue mixing and concreting operations when the descending ambient air temperature reaches 40°F (4ºC), and do not resume until an ascending ambient air temperature reaches 35°F (2ºC).

If the Engineer permits placing concrete during cold weather, aggregates may be heated by either steam or dry heat before placing them in the mixer. Use an apparatus that heats the weight uniformly and is so arranged as to preclude the possible occurrence of overheated areas which might injure the materials. Do not heat aggregates directly by gas or oil flame or on sheet metal over fire. Aggregates that are heated in bins, by steam-coil or water-coil heating, or by other methods not detrimental to the aggregates may be used. The use of live steam on or through binned aggregates is not permitted. Unless otherwise authorized, the temperature of the mixed concrete must be at least 55°F (13ºC), but not more than 70°F (21ºC) at the time of placing it in the forms. With approval by the engineer, the temperature of the concrete may be up to 5°F (3ºC) below or above this range. Do not place concrete when there is a probability of air temperatures being more than 25°F (14°C) below the temperature of the concrete during the first 24 hours after placement unless insulation is provided for both the deck and the girders. Do not, under any circumstances, continue concrete operations if the ambient air temperature is less than 20°F (-7ºC).

If the ambient air temperature is 35°F (2ºC) or less at the time the concrete is placed, the Engineer may require that the water and the aggregates be heated to at least 70°F (21ºC), but not more than 120°F (49ºC).

Do not place concrete on frozen subgrade or use frozen aggregates in the concrete.

(4) Placing Concrete in Hot Weather. When the ambient temperature is above 90°F (32°C), cool the forms, reinforcing steel, steel beam flanges, and other surfaces which will come in contact with the mix to below 90°F (32°C) by means of a water spray or other approved methods. For Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete, cool the concrete mixture to maintain the temperature immediately before placement between 55°F (13ºC) and 70°F (21ºC). With approval by the engineer, the temperature of the concrete may be up to 5°F (3ºC) below or above this range.

The temperature of the concrete at time of placement shall be maintained within the specified temperature range by any combination of the following:

- Shading the materials storage areas or the production equipment.
- Cooling the aggregates by sprinkling with potable water.
- Cooling the aggregates or water by refrigeration or replacing a portion or all of the mix water with ice that is flaked or crushed to the extent that the ice will completely melt during mixing of the concrete.
- Liquid nitrogen injection.

402.6 INSPECTION AND TESTING.

Obtain samples of fresh concrete for the determination of slump, temperature, weight per cubic yard (meter), and percent of air from the site the concrete is placed.

The Engineer will cast, store, and test strength test specimens in sets of 5. See requirements in **Table 402-4**.

The Department will conduct the sampling and test the samples according to **Section 2500** and **Table 402-4**.

Test the first truckload at truck discharge. Test that load and subsequent loads at the point of deposit on the bridge deck. If potential problems are apparent at the discharge of any truck, test concrete at truck discharge prior to deposit on the bridge deck.

TABLE 402-4, Sampling and Testing Frequency Chart

Tests Required (Record to)	Test Method	CMS	Verification Samples and Tests	Acceptance Samples and Tests
Slump (0.25 in or 5 mm)	KT-21	a	Each of first 3 truckloads for any individual placement, then 1 of every 2 truckloads	
Temperature (1°F or 0.5°C)	KT-17	a	Every truckload, measured at the truck discharge, and from each sample made for slump determination.	
Mass (0.1 lb or 50 g)	KT-20	a	Every 4 truckloads	
Air Content (0.25%)	KT-18 or KT-19	a	Each of first 3 truckloads for any individual placement, then 1 of every 4 truckloads	
Cylinders (1 lbf or 1 N; 0.1 in or 1 mm; 1 psi or 0.01 MPa)	KT-22 and AASHTO T 22	VER	Make at least five cylinders per pour or major mix design change. Three test cylinders are to be cured according to KT-22 and two test cylinders will be field-cured. Store the field-cured cylinders on or adjacent to the bridge. Protect all surfaces of the cylinders from the elements in as near as possible the same way as the deck concrete. Test the field-cured cylinders at the same age as the standard-cured cylinders.	
Density of Fresh Concrete (0.1 lb/cu ft (1 kg/cu m) or 0.1% of optimum density)	KT-36	ACI		b,c: 1 per 150 cu yd (150 cu m) for thin overlays and bridge deck surfacing.

Note a: "Type Insp" must = "ACC" when the assignment of a pay quantity is being made. "ACI" when recording test values for additional acceptance information.
Note b: Normal operation. Minimum frequency for exceptional conditions may be reduced by the District Materials Engineer on a project basis, written justification shall be made to the Chief of the Bureau of Materials and Research and placed in the project documents. (Multi-Level Frequency Chart (see page 17, Appendix A of Construction Manual, Part V).
Note c: Applicable only when specifications contain those requirements.

The Engineer will reject concrete that does not comply with specified requirements.

The Engineer will permit occasional deviations below the specified cement content, if it is due to the air content of the concrete exceeding the designated air content, but only up to the plus 1.0 percent tolerance in the air content. Continuous operation below the specified cement content for any reason is not permitted.

As the work progresses, the Engineer reserves the right to require the Contractor to change the proportions if conditions warrant such changes to produce a satisfactory mix. Any such changes may be made within the limits of the Specifications at no additional compensation to the Contractor.

06-15-06 M&R (REK)

PCC000078 ACCP	Conc (MA) Grade 3.5 (24) (AE) (LC-HPC)	cu yd	(cu m)	90M-7275
PCC000079 ACCP	Conc (CF) Grade 3.5 (24) (AE) (LC-HPC)	cu yd	(cu m)	90M-7275

7295

KANSAS DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION TO THE
STANDARD SPECIFICATIONS 1990 EDITION

NOTE: This special provision is generally written in the imperative mood. The subject, "the *Contractor*" is implied. Also implied in this language are "*shall*", "*shall be*", or similar words and phrases. The word "*will*" generally pertains to decisions or actions` of the Kansas Department of Transportation.

Section 402. Delete the Section and replace with this:

SECTION 402

LOW CRACKING HIGH PERFORMANCE - CONCRETE

402.1 DESCRIPTION

Provide the grades of concrete specified in the Contract Documents.

402.2 MATERIALS

Coarse, fine, and mixed aggregates ....Special Provision 90M-7339
Admixtures ....Section 1400
Cement ....Special Provision 90M-212 (latest revision)
Water..Section 2400

402.3 CONCRETE MIX DESIGN

a. General. The Contractor (or a prospective bidder) may contact the District Materials Engineer or the Bureau of Materials and Research for any available information to help determine approximate proportions which will produce concrete having the required characteristics.

The Contractor is responsible for the actual proportions of the concrete mix. If the Contractor requests (in writing), the Engineer will assist in the design of the concrete mix. A copy of the final design is to be submitted to the District Materials Engineer and Bureau of Materials and Research.

Design the concrete mixes specified in the Contract Documents. Design concrete mixes that comply with these requirements:

b. Air-Entrained Concrete for Bridge Decks. Design air-entrained concrete for structures according to these requirements:

TABLE 402-1, Air-Entrained Concrete for Bridge Decks

Grade of Concrete Type of Aggregate (Section 1100)	lb. (kg) of Cement per cu yd (cu m) of Concrete, min/max	lb (kg) of Water per lb (kg) of Cement, max*	Designated Air Content Percent by Volume**
Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC))			
MA-4	500 (300)/ 535(317)	0.42	8.0 ± 1.0

*Maximum limit of lb. (kg) of water per lb. (kg) of cement includes free water in aggregates, but excludes water of absorption of the aggregates.

** Concrete with an air content less than 6.5% or greater than 9.5% shall be rejected.

c. Portland Cement. Select the type of portland cement specified in the Contract Documents. <u>No mineral admixtures are permitted for Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete.</u>

d. Design Air Content. Use the middle of the specified air content range for the design of air-entrained concrete.

e. Admixtures for Acceleration, Air-Entraining, Plasticizing, Set Retardation, and Water Reduction. Use the dosages recommended by the admixture manufacturers. Incorporate and mix the admixtures into the concrete mixtures according to the manufacturer's recommendations.

Determine the quantity of each admixture for the concrete mix design.

If another admixture is added to an air-entrained concrete mixture, determine if it is necessary to adjust the air-entraining admixture dosage to maintain the specified air content.

Admixtures containing chloride ion (CL) in excess of 0.1 percent by mass of the admixture shall not be used in Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete.

(1) Accelerating Admixture. If specified in the Contract Documents, or in situations that involve contact with reinforcing steel and require early strength development to expedite opening to traffic, a non-chloride accelerator may be appropriate. The Engineer may approve the use of a Type C or E accelerating admixture.

(2) Air-Entraining Admixture. If specified, use air-entraining admixture in the concrete mixture.

If the concrete mixture also contains a plasticizing or a water reducing, high range admixture, use only a vinsol resin or tall oil based air-entraining admixture.

(3) Plasticizing Admixture. Include a batching sequence in the concrete mix design. Consider the location of the concrete plant in relation to the job site, and identify the approximate quantity, when and at what location the plasticizing admixture is added to the concrete mixture. Do not add water after the plasticizing admixture is added to the concrete mixture.

Manufacturers of plasticizing admixtures may recommend mixing revolutions beyond the limits specified in **subsection 402.5**. If necessary, address the additional mixing revolutions (the Engineer will allow up to 60 additional revolutions) in the concrete mix design.

Accomplish slump control in the field by redosing. If time and temperature limits are not exceeded, and if at least 30 mixing revolutions remain, the Engineer will allow redosing with up to 50 percent of the original dose. See also subsection 402.5a.

(4) Water Reduction and Set Retardation. If unfavorable weather or other conditions adversely affect the placing and finishing properties of the concrete mix, the Engineer may allow the use of water reducing and set retarding admixtures. If the Engineer approves the use of water reducing and set retarding admixtures, their continued use depends on their performance. It is the Contractor's responsibility to insure that the admixtures will work as intended without detrimental effects.

(5) Adjust the mix designs during the course of the work when necessary to ensure compliance with the specified fresh and hardened concrete properties. Only permit such modifications after trial batches to demonstrate that the adjusted mix design will result in concrete that complies with the specified concrete properties.

The Engineer will allow adjustments to the dose rate of air entraining, water-reducing and retarding chemical admixtures to compensate for environmental changes during placement without a new concrete mix design or qualification batch.

f. Designated Slump. Designate a slump for each concrete mix design that is within these limits:

TABLE 402-2, Designated Slump

Type of Work:	**Designated Slump** in. (mm)	**Maximum Allowable Slump** in. (mm)
Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC))	1 ½ - 3 (36-75)	4 (100)

NOTE: When high range water reducing admixtures are used with Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete mixtures, **Table 402-2** slump limits shall not be exceeded.

g. Approval of Concrete Mix Designs. Submit all concrete mix designs to the Engineer and the Research Development Engineer for review and approval. Submit completed volumetric mix designs on KDOT Form No. 694 (or other forms approved by the District Materials Engineer).

Do not place any concrete on the Project until the Engineer approves the concrete mix designs, qualification batch, and qualification slab. Once the Engineer approves the concrete mix design, do not make changes without the Engineer's approval (see Section 402.5b).

402.4 REQUIREMENTS FOR COMBINED MATERIALS.

a. Measurements for Proportioning Materials.

(1) Cement. Measure cement as packed by the manufacturer. A sack of cement is considered as 0.04 cubic yards (0.03 cu m) weighing 94 pounds (42.6 kg) net. Measure bulk cement by weight. In either case, the measurement must be accurate to within 0.5 percent throughout the range of use.

(2) Water. Measure the mixing water by weight or by volume. In either case the measurement must be accurate to within 1 percent throughout the range of use.

(3) Aggregates. Measure the aggregates by weight. The measurement must be accurate to within 0.5 percent throughout the range of use.

(4) Admixtures. Measure liquid admixtures by weight or volume. If liquid admixtures are used in small quantities in proportion to the cement as in the case of air-entraining agents, use readily adjustable mechanical dispensing equipment capable of being set to deliver the required

quantity and to cut off the flow automatically when this quantity is discharged. The measurement must be accurate to within 3 percent of the quantity required.

b. Testing of Aggregates. Testing Aggregates at the Batch Site. Provide the Engineer with reasonable facilities at the batch site for obtaining samples of the aggregates. Provide adequate and safe laboratory facilities at the batch site that will allow the Engineer to test the aggregates for compliance with the specified requirements.

The Department will sample and test aggregates from each source to determine their compliance with specifications. Batching of the concrete mixture is not permitted until the Engineer has determined that the aggregates comply with the specifications. The Department will conduct the sampling at the batching site, and test the samples according to the Frequency Testing Chart in Part V of the KDOT Construction Manual. For QC/QA Contracts, the Contractor will determine testing intervals within the specified minimum frequency.

After initial testing is complete and the Engineer has determined that the aggregate process control is satisfactory, use the aggregates concurrently with sampling and testing as long as tests indicate compliance with specifications. During the batching operations, sample the aggregates as near the point of batching as feasible. Sample from the stream as the storage bins or weigh hoppers are loaded. If samples cannot be reasonably taken from the stream, take them from approved stockpiles. If test results indicate that an aggregate does not comply with specifications, cease concrete production using that aggregate. Unless a tested and approved stockpile for that aggregate is available at the batch plant, do not use any additional aggregate from that source and specified grading until subsequent sampling and testing of that aggregate indicate compliance with specifications. When tests are completed and the Engineer is satisfied that process control is again adequate, production of concrete using aggregates sampled and tested concurrently with production may resume.

c. Handling of Materials.

(1) Approved stockpiles are permitted only at the batch plant and only for small concrete placements or for the purpose of maintaining concrete production. Mark the approved stockpile with an "Approved Materials" sign. Provide a suitable stockpile area at the batch plant so that aggregates are stored without detrimental segregation or contamination. Unless otherwise approved by the Engineer, no more than 250 tons (Mg) of coarse aggregate and no more than 250 tons (Mg) of fine aggregate tested and approved by the Engineer may be stockpiled at the plant. If mixed aggregate is used, limit the approved stockpile to 500 tons (Mg), the size of each being proportional to the amount of each aggregate to be used in the mix.

Load aggregates into the mixer in such a manner that no material foreign to the concrete or material capable of changing the desired proportions is included. In the event 2 or more sizes or types of coarse or fine aggregates are used on the same project, only 1 size or type of each aggregate may be used on 1 continuous concrete placement.

(2) Segregation. Do not use segregated aggregates until they are thoroughly re-mixed and the resultant pile is of uniform and acceptable grading at any point from which a representative sample is taken.

(3) Cement. Protect cement in storage or stockpiled on the site from any damage by climatic conditions which would change the characteristics or usability of the material.

(4) Moisture. If the moisture content of an approved aggregate remains constant within a tolerance of 0.5 percent plus or minus from the average of that day, they may be used. However, if the moisture content in the aggregate varies by more than the above tolerance, then take whatever corrective measures are necessary to bring the moisture to a constant and uniform quantity before any more concrete is placed. This may be accomplished by handling or manipulating the stockpiles to reduce the moisture content or by adding moisture to the stockpiles in a manner that will produce a uniform moisture content through all portions of the stockpile.

If plant equipment includes an approved accurate moisture-determining device which will make possible the determination of the free moisture in the aggregates and provisions are made for batch to batch correction of the amount of water and the weight of aggregates added, the above requirements relative to handling or manipulating the stockpiles for moisture control will be waived. However, any procedure used will not relieve the producer of the responsibility for delivery of concrete of uniform slump within the limits specified.

Do not use aggregate in the form of frozen lumps in the manufacture of concrete.

(5) Separation of Materials in Tested and Approved Stockpiles. Only use KDOT Approved Materials. Provide separate means for storing materials approved by the Department. If the producer elects to use KDOT Approved Materials for other work for his own convenience, during the progress of a project requiring KDOT Approved Materials, he must so inform the Engineer and agree to pay all costs of having the additional materials tested.

Clean all conveyors, bins and hoppers of unapproved materials before starting to manufacture concrete for the work.

402.5 MIXING, DELIVERY, AND PLACEMENT LIMITATIONS.

a. Concrete Batching, Mixing, and Delivery. Batch and mix the concrete in a central-mix plant, in a truck mixer, or in a drum mixer at the work site. Provide plant capacity and delivery capacity sufficient to insure continuous delivery at the rate required. The rate of delivery of concrete during concreting operations must provide for the proper handling, placing and finishing of the concrete.

The Engineer must approve the concrete plant/batch site before any concrete is produced for the project. The Engineer will inspect and review the equipment, the method of storing and handling of materials, the production procedures, and the transportation and rate of delivery of concrete from the plant to the point of use. The Engineer will grant approval of the concrete plant/batch site based on compliance with the specified requirements. The Engineer may, at any time, rescind permission to use concrete from a previously approved concrete plant/batch site upon failure to comply with the specified requirements.

The mixing drum must be clean before it is charged with the concrete mixture. Charge the batch into the mixing drum so that a portion of the water is in the drum before the aggregates and cement. The flow of water into the drum throughout the batching operation must be uniform, with all of the water in the drum by the end of the first 15 seconds of the mixing cycle. Keep the throat of the drum free of accumulations that restrict the flow of materials into the drum.

Do not exceed the rated capacity (cubic yards (cu m) shown on the manufacturer's plate on the mixer) of the mixer when batching the concrete. However, the Engineer will allow an overload of up to 10 percent above the rated capacity for central-mix plants and drum mixers at the work site, provided the concrete test data for strength, segregation, and uniform consistency are satisfactory, and no concrete is spilled during the mixing cycle.

Operate the mixing drum at the speed specified by the mixer's manufacturer (shown on the manufacturer's plate on the mixer).

Mixing time is measured from the time all materials, except water, are in the drum. If it is necessary to increase the mixing time to obtain the specified percent of air in air-entrained concrete, the Engineer will determine the mixing time.

If the concrete is mixed in a central-mix plant or a drum mixer at the work site, mix the batch at least 60 seconds, but not more than 5 minutes at mixing speed, with the total mixing revolutions not exceeding 60 revolutions. Mixing time begins after all materials, except water, are in the drum, and ends when the discharge chute opens. Transfer time in multiple drum mixers is included in mixing time. Mix time may be reduced for plants utilizing high performance mixing drums provided satisfactory evidence can be provided to the Engineer that thoroughly mixed and uniform concrete is being produced with the proposed mix time. Performance of the plant must conform to the requirements of Table A1.1, of ASTM C 94, Standard Specification for Ready Mixed Concrete. Five of the six tests listed in Table A1.1 must be within the limits of the specification to indicate that uniform concrete is being produced.

If the concrete is mixed in a truck mixer, mix the batch at least 70 revolutions, but not more than 100 revolutions of the drum or blades at mixing speed. After the mixing is completed, set the truck mixer drum at agitating speed. Unless the mixing unit is equipped with an accurate and dependable device that will indicate and control the number of revolutions at mixing speed, perform the mixing at the batch plant and operate the mixing unit at agitating speed while traveling from the plant to the work site. Do not exceed 350 total revolutions (mixing and agitating).

If a truck mixer or truck agitator is used to transport concrete that was completely mixed in a stationary central mixer, agitate the concrete while transporting at the agitating speed specified by the manufacturer of the equipment (shown on the manufacturer's plate on the equipment). Do not exceed 250 total revolutions (additional re-mixing and agitating).

Provide a time slip, for each batch of concrete delivered at the work site, issued at the batching plant that bears the time of charging of the mixer drum with cement and aggregates. On paving projects and other high volume work, the Engineer will determine the haul time and thereafter make random checks, and tickets for every load are not required.

If non-agitating equipment is used for transportation of concrete, provide approved covers for protection against the weather when required by the Engineer.

Place non-agitated concrete within 30 minutes of adding the cement to the water.

TABLE 402-3, Ambient Air Temperature and Agitated Concrete Placement Time

T_{air} = Ambient Air Temperature at Time of Batching °F (°C)	Time limit agitated concrete must be placed within, after the addition of cement to water (hours)	Admixtures
$T_{air} < 75$ (24)	1 ½	None
75 (24) $\leq T_{air} <$ 90 (32)	1	None
75 (24) $\leq T_{air} <$ 90 (32)	1 ½	Set Retarder
90 (32) $\leq T_{air}$	1	None

Note: Maximum concrete temperature is 70°F (21°C) [75°F (24°C) with approval of the engineer].

Do not use concrete that has developed its initial set. Regardless of the speed of delivery and placement, the Engineer will suspend the concreting operations until corrective measures are taken if there is evidence that the concrete can not be adequately consolidated.

Adding water to concrete after the initial mixing is prohibited, with this exception: If the concrete is delivered to the work site in a truck mixer, the Engineer will allow water [up to 2 gallons per cubic yard (10 L/cu m) (16 pounds per cubic yard) (9.6 kg/cu m)] be withheld from the mixture at the batch site, and if needed, added at the work site to adjust the slump to comply with the specified requirements. Determine the need for additional water as soon as the load arrives at the construction site. Use a calibrated water-measuring device to add the water, and add the water to the entire load. Do not add more water than was withheld at the batch site. After the additional water is added, turn the drum or blades an additional 20 to 30 revolutions at mixing speed. The Engineer will supervise the adding of water to the load, and will allow this procedure only once per load. See also subsection 402.3e(3).

b. Placement Limitations

(1) For Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete, qualify a field batch (one truckload or at least 6 cubic yards (5 cu m)) at least 35 days prior to commencement of placement of the bridge decks. Produce the qualification batch from the same plant that will supply the job concrete. Haul time to the jobsite should be simulated prior to discharge of the concrete for testing. Prior to placing concrete in the qualification slab and on the job, submit documentation to the Engineer verifying that the qualification batch concrete meets the requirements for air content, slump, temperature of plastic concrete, compressive strength, unit weight, and other testing as required by the Engineer.

Before the concrete mixture with plasticizing admixture is used on the project, determine the air content of the qualification batch. Monitor the slump, air content, temperature, and workability at initial batching and estimated time of concrete placement. If these properties are not adequate, repeat the qualification batch until it can be demonstrated that the mix is within acceptable limits as specified in this document.

(2) Placing Concrete at Night. Do not mix, place or finish concrete without sufficient natural light, unless an adequate and artificial lighting system approved by the Engineer is provided.

(3) Placing Concrete in Cold Weather. Unless authorized otherwise by the Engineer, discontinue mixing and concreting operations when the descending ambient air temperature reaches 40°F (4ºC), and do not resume until an ascending ambient air temperature reaches 35°F (2ºC).

If the Engineer permits placing concrete during cold weather, aggregates may be heated by either steam or dry heat before placing them in the mixer. Use an apparatus that heats the weight uniformly and is so arranged as to preclude the possible occurrence of overheated areas which might injure the materials. Do not heat aggregates directly by gas or oil flame or on sheet metal over fire. Aggregates that are heated in bins, by steam-coil or water-coil heating, or by other methods not detrimental to the aggregates may be used. The use of live steam on or through binned aggregates is not permitted. Unless otherwise authorized, the temperature of the mixed concrete must be at least 55°F (13ºC), but not more than 70°F (21ºC) at the time of placing it in the forms. With approval by the engineer, the temperature of the concrete may be up to 5°F (3ºC) below or above this range. Do not place concrete when there is a probability of air temperatures being more than 25°F (14°C) below the temperature of the concrete during the first 24 hours after placement unless insulation is provided for both the deck and the girders. Do not, under any circumstances, continue concrete operations if the ambient air temperature is less than 20°F (-7°C).

If the ambient air temperature is 35°F (2°C) or less at the time the concrete is placed, the Engineer may require that the water and the aggregates be heated to at least 70°F (21°C), but not more than 120°F (49°C).

Do not place concrete on frozen subgrade or use frozen aggregates in the concrete.

(4) Placing Concrete in Hot Weather. When the ambient temperature is above 90°F (32°C), cool the forms, reinforcing steel, steel beam flanges, and other surfaces which will come in contact with the mix to below 90°F (32°C) by means of a water spray or other approved methods. For Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete, cool the concrete mixture to maintain the temperature immediately before placement between 55°F (13°C) and 70°F (21°C). With approval by the engineer, the temperature of the concrete may be up to 5°F (3°C) below or above this range.

The temperature of the concrete at time of placement shall be maintained within the specified temperature range by any combination of the following:

- Shading the materials storage areas or the production equipment.
- Cooling the aggregates by sprinkling with potable water.
- Cooling the aggregates or water by refrigeration or replacing a portion or all of the mix water with ice that is flaked or crushed to the extent that the ice will completely melt during mixing of the concrete.
- Liquid nitrogen injection.

402.6 INSPECTION AND TESTING.

Obtain samples of fresh concrete for the determination of slump, temperature, weight per cubic yard (meter), and percent of air from the site the concrete is placed.

The Engineer will cast, store, and test strength test specimens in sets of 5. See requirements in **Table 402-4**.

The Department will conduct the sampling and test the samples according to **Section 2500** and **Table 402-4**.

Test the first truckload at truck discharge. Test that load and subsequent loads at the point of deposit on the bridge deck. If potential problems are apparent at the discharge of any truck, test concrete at truck discharge prior to deposit on the bridge deck.

90M-7338
Sheet 9 of 9
402

TABLE 402-4, Sampling and Testing Frequency Chart

Tests Required (Record to)	Test Method	CMS	Verification Samples and Tests	Acceptance Samples and Tests
Slump (0.25 in or 5 mm)	KT-21	a	Each of first 3 truckloads for any individual placement, then 1 of every 2 truckloads	
Temperature (1°F or 0.5°C)	KT-17	a	Every truckload, measured at the truck discharge, and from each sample made for slump determination.	
Mass (0.1 lb or 50 g)	KT-20	a	Every 4 truckloads	
Air Content (0.25%)	KT-18 or KT-19	a	Each of first 3 truckloads for any individual placement, then 1 of every 4 truckloads	
Cylinders (1 lbf or 1 N; 0.1 in or 1 mm; 1 psi or 0.01 MPa)	KT-22 and AASHTO T 22	VER	Make at least five cylinders per pour or major mix design change. Three test cylinders are to be cured according to KT-22 and two test cylinders will be field-cured. Store the field-cured cylinders on or adjacent to the bridge. Protect all surfaces of the cylinders from the elements in as near as possible the same way as the deck concrete. Test the field-cured cylinders at the same age as the standard-cured cylinders.	
Density of Fresh Concrete (0.1 lb/cu ft (1 kg/cu m) or 0.1% of optimum density)	KT-36	ACI		b,c: 1 per 150 cu yd (150 cu m) for thin overlays and bridge deck surfacing.

Note a: "Type Insp" must = "ACC" when the assignment of a pay quantity is being made. "ACI" when recording test values for additional acceptance information.
Note b: Normal operation. Minimum frequency for exceptional conditions may be reduced by the District Materials Engineer on a project basis, written justification shall be made to the Chief of the Bureau of Materials and Research and placed in the project documents. (Multi-Level Frequency Chart (see page 17, Appendix A of Construction Manual, Part V).
Note c: Applicable only when specifications contain those requirements.

The Engineer will reject concrete that does not comply with specified requirements.

The Engineer will permit occasional deviations below the specified cement content, if it is due to the air content of the concrete exceeding the designated air content, but only up to the plus 1.0 percent tolerance in the air content. Continuous operation below the specified cement content for any reason is not permitted.

As the work progresses, the Engineer reserves the right to require the Contractor to change the proportions if conditions warrant such changes to produce a satisfactory mix. Any such changes may be made within the limits of the Specifications at no additional compensation to the Contractor.

08-02-06 M&R (REK)

PCC000078	Conc (MA) Grade 3.5 (24) (AE) (LC-HPC)	cu yd	(cu m)	90M-7275	ACCP
PCC000079	Conc (CF) Grade 3.5 (24) (AE) (LC-HPC)	cu yd	(cu m)	90M-7275	ACCP

KANSAS DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION TO THE
STANDARD SPECIFICATIONS 1990 EDITION

NOTE: This special provision is generally written in the imperative mood. The subject, "the *Contractor*" is implied. Also implied in this language are "*shall*", "*shall be*", or similar words and phrases. The word "*will*" generally pertains to decisions or actions` of the Kansas Department of Transportation.

Section 402. Delete the Section and replace with this:

SECTION 402

LOW CRACKING HIGH PERFORMANCE - CONCRETE

402.1 DESCRIPTION

Provide the grades of concrete specified in the Contract Documents.

402.2 MATERIALS

Coarse, fine, and mixed aggregates ....Special Provision 90P-5085
Admixtures ....Section 1400
Cement ....Special Provision 90M/P-212 (latest revision)
Water...Section 2400

402.3 CONCRETE MIX DESIGN

a. General. The Contractor (or a prospective bidder) may contact the District Materials Engineer or the Bureau of Materials and Research for any available information to help determine approximate proportions which will produce concrete having the required characteristics.

The Contractor is responsible for the actual proportions of the concrete mix. If the Contractor requests (in writing), the Engineer will assist in the design of the concrete mix. A copy of the final design is to be submitted to the District Materials Engineer and Bureau of Materials and Research.

Design the concrete mixes specified in the Contract Documents. Design concrete mixes that comply with these requirements:

b. Air-Entrained Concrete for Bridge Decks. Design air-entrained concrete for structures according to these requirements:

TABLE 402-1, Air-Entrained Concrete for Bridge Decks

Grade of Concrete Type of Aggregate (Section 1100)	lb. (kg) of Cement per cu yd (cu m) of Concrete, min/max	lb (kg) of Water per lb (kg) of Cement, max*	Designated Air Content Percent by Volume**
Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC))			
MA-4	500 (300)/ 535(317)	0.42	8.0 ± 1.0

*Maximum limit of lb. (kg) of water per lb. (kg) of cement includes free water in aggregates, but excludes water of absorption of the aggregates.
** Concrete with an air content less than 6.5% or greater than 9.5% shall be rejected.

c. Portland Cement. Select the type of portland cement specified in the Contract Documents. <u>No mineral admixtures are permitted for Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete.</u>

d. Design Air Content. Use the middle of the specified air content range for the design of air-entrained concrete.

e. Admixtures for Air-Entrainment and Water Reduction. Use the dosages recommended by the admixture manufacturers to determine the quantity of each admixture for the concrete mix design. Incorporate and mix the admixtures into the concrete mixtures according to the manufacturer's recommendations.

No set retarding or accelerating admixtures are permitted for use in Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete. These include Type B, C, D, E, and G chemical admixtures as defined by ASTM C 494/C 494M – 05a.

Admixtures containing chloride ion (CL) in excess of 0.1 percent by mass of the admixture shall not be used in Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete.

(1) Air-Entraining Admixture. If specified, use an air-entraining admixture in the concrete mixture. If another admixture is added to an air-entrained concrete mixture, determine if it is necessary to adjust the air-entraining admixture dosage to maintain the specified air content. Use only a vinsol resin or tall oil based air-entraining admixture.

(2) Water-Reducing Admixture. Use a Type A water reducer or a Type F high-range water reducer when necessary to ensure compliance with the specified fresh and hardened concrete properties.

Include a batching sequence in the concrete mix design. Consider the location of the concrete plant in relation to the job site, and identify the approximate quantity, when and at what location the water-reducing admixture is added to the concrete mixture.

Manufacturer may recommend mixing revolutions beyond the limits specified in **subsection 402.5**. If necessary and with the approval of the Engineer, address the additional mixing revolutions (the Engineer will allow up to 60 additional revolutions) in the concrete mix design.

Slump control may be accomplished in the field by redosing. If time and temperature limits are not exceeded, and if at least 30 mixing revolutions remain, the Engineer will allow redosing with up to 50 percent of the original dose. For additional slump control measures see subsection 402.5a.

(3) Adjust the mix designs during the course of the work when necessary to ensure compliance with the specified fresh and hardened concrete properties. Only permit such modifications after trial batches to demonstrate that the adjusted mix design will result in concrete that complies with the specified concrete properties.

The Engineer will allow adjustments to the dose rate of air entraining and water-reducing chemical admixtures to compensate for environmental changes during placement without a new concrete mix design or qualification batch.

f. Designated Slump. Designate a slump for each concrete mix design that is within these limits:

TABLE 402-2, Designated Slump

Type of Work:	Designated Slump inch (mm)	Maximum Allowable Slump inch (mm)
Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC))	1 ½ - 3 (36-75)	4 (100)

NOTE: When high range water reducing admixtures are used with Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete mixtures, **Table 402-2** slump limits shall not be exceeded.

g. Approval of Concrete Mix Designs. Submit all concrete mix designs to the Engineer and the Research Development Engineer for review and approval. Submit completed volumetric mix designs on KDOT Form No. 694 (or other forms approved by the District Materials Engineer).

Do not place any concrete on the Project until the Engineer approves the concrete mix designs, qualification batch, and qualification slab. Once the Engineer approves the concrete mix design, do not make changes without the Engineer's approval (see Section 402.5b).

402.4 REQUIREMENTS FOR COMBINED MATERIALS.

a. Measurements for Proportioning Materials.

(1) Cement. Measure bulk cement by weight. The measurement must be accurate to within 0.5 percent throughout the range of use.

(2) Water. Measure the mixing water by weight or by volume. In either case the measurement must be accurate to within 1 percent throughout the range of use.

(3) Aggregates. Measure the aggregates by weight. The measurement must be accurate to within 0.5 percent throughout the range of use.

(4) Admixtures. Measure liquid admixtures by weight or volume. If liquid admixtures are used in small quantities in proportion to the cement as in the case of air-entraining agents, use readily adjustable mechanical dispensing equipment capable of being set to deliver the required quantity and to cut off the flow automatically when this quantity is discharged. The measurement must be accurate to within 3 percent of the quantity required.

b. Testing of Aggregates. Testing Aggregates at the Batch Site. Provide the Engineer with reasonable facilities at the batch site for obtaining samples of the aggregates. Provide adequate and safe laboratory facilities at the batch site that will allow the Engineer to test the aggregates for compliance with the specified requirements.

KDOT will sample and test aggregates from each source to determine their compliance with specifications. Batching of the concrete mixture is not permitted until the Engineer has determined that the aggregates comply with the specifications. KDOT will conduct the sampling at the batching site, and test the samples according to the Frequency Testing Chart in Part V of the KDOT Construction Manual. For QC/QA Contracts, the Contractor will determine testing intervals within the specified minimum frequency.

After initial testing is complete and the Engineer has determined that the aggregate process control is satisfactory, use the aggregates concurrently with sampling and testing as long as tests indicate compliance with specifications. During the batching operations, sample the aggregates as near the point of batching as feasible. Sample from the stream as the storage bins or weigh hoppers are loaded. If samples cannot be reasonably taken from the stream, take them from approved stockpiles. If test results indicate that an aggregate does not comply with specifications, cease concrete production using that aggregate. Unless a tested and approved stockpile for that aggregate is available at the batch plant, do not use any additional aggregate from that source and specified grading until subsequent sampling and testing of that aggregate indicate compliance with specifications. When tests are completed and the Engineer is satisfied that process control is again adequate, production of concrete using aggregates sampled and tested concurrently with production may resume.

c. Handling of Materials.

(1) Aggregate Stockpiles. Approved stockpiles are permitted only at the batch plant and only for small concrete placements or for the purpose of maintaining concrete production. Mark the approved stockpile with an “Approved Materials” sign. Provide a suitable stockpile area at the batch plant so that aggregates are stored without detrimental segregation or contamination. Unless otherwise approved by the Engineer, no more than 250 tons (Mg) of coarse aggregate and no more than 250 tons (Mg) of fine aggregate tested and approved by the Engineer may be stockpiled at the plant. If mixed aggregate is used, limit the approved stockpile to 500 tons (Mg), the size of each being proportional to the amount of each aggregate to be used in the mix.

Load aggregates into the mixer in such a manner that no material foreign to the concrete or material capable of changing the desired proportions is included. In the event 2 or more sizes or types of coarse or fine aggregates are used on the same project, only 1 size or type of each aggregate may be used on 1 continuous concrete placement.

(2) Segregation. Do not use segregated aggregates until they are thoroughly re-mixed and the resultant pile is of uniform and acceptable grading at any point from which a representative sample is taken.

(3) Cement. Protect cement in storage or stockpiled on the site from any damage by climatic conditions which would change the characteristics or usability of the material.

(4) Moisture. If the moisture content of an approved aggregate remains constant within a tolerance of 0.5 percent plus or minus from the average of that day, they may be used. However, if the moisture content in the aggregate varies by more than the above tolerance, then take whatever corrective measures are necessary to bring the moisture to a constant and uniform quantity before any more concrete is placed. This may be accomplished by handling or manipulating the stockpiles to reduce the moisture content or by adding moisture to the stockpiles in a manner that will produce a uniform moisture content through all portions of the stockpile.

If plant equipment includes an approved accurate moisture-determining device which will make possible the determination of the free moisture in the aggregates and provisions are made for batch to batch correction of the amount of water and the weight of aggregates added, the above requirements relative to handling or manipulating the stockpiles for moisture control will be waived. However, any procedure used will not relieve the producer of the responsibility for delivery of concrete of uniform slump within the limits specified.

Do not use aggregate in the form of frozen lumps in the manufacture of concrete.

(5) Separation of Materials in Tested and Approved Stockpiles. Only use KDOT Approved Materials. Provide separate means for storing materials approved by KDOT. If the producer elects to use KDOT Approved Materials for other work for his own convenience, during the progress of a project requiring KDOT Approved Materials, he must so inform the Engineer and agree to pay all costs of having the additional materials tested.

Clean all conveyors, bins and hoppers of unapproved materials before starting to manufacture concrete for the work.

402.5 MIXING, DELIVERY, AND PLACEMENT LIMITATIONS.

a. Concrete Batching, Mixing, and Delivery. Batch and mix the concrete in a central-mix plant, in a truck mixer, or in a drum mixer at the work site. Provide plant capacity and delivery capacity sufficient to insure continuous delivery at the rate required. The rate of delivery of concrete during concreting operations must provide for the proper handling, placing and finishing of the concrete.

The Engineer must approve the concrete plant/batch site before any concrete is produced for the project. The Engineer will inspect and review the equipment, the method of storing and handling of materials, the production procedures, and the transportation and rate of delivery of concrete from the plant to the point of use. The Engineer will grant approval of the concrete plant/batch site based on compliance with the specified requirements. The Engineer may, at any time, rescind permission to use concrete from a previously approved concrete plant/batch site upon failure to comply with the specified requirements.

The mixing drum must be clean before it is charged with the concrete mixture. Charge the batch into the mixing drum so that a portion of the water is in the drum before the aggregates and cement. The flow of water into the drum throughout the batching operation must be uniform, with all of the water in the drum by the end of the first 15 seconds of the mixing cycle. Keep the throat of the drum free of accumulations that restrict the flow of materials into the drum.

Do not exceed the rated capacity (cubic yards (cu m) shown on the manufacturer's plate on the mixer) of the mixer when batching the concrete. However, the Engineer will allow an overload of up to 10 percent above the rated capacity for central-mix plants and drum mixers at the work site, provided the concrete test data for strength, segregation, and uniform consistency are satisfactory, and no concrete is spilled during the mixing cycle.

Operate the mixing drum at the speed specified by the mixer's manufacturer (shown on the manufacturer's plate on the mixer).

Mixing time is measured from the time all materials, except water, are in the drum. If it is necessary to increase the mixing time to obtain the specified percent of air in air-entrained concrete, the Engineer will determine the mixing time.

If the concrete is mixed in a central-mix plant or a drum mixer at the work site, mix the batch at least 60 seconds, but not more than 5 minutes at mixing speed, with the total mixing revolutions not exceeding 60 revolutions. Mixing time begins after all materials, except water, are in the drum, and ends when the discharge chute opens. Transfer time in multiple drum mixers is included in mixing time. Mix time may be reduced for plants utilizing high performance mixing drums provided satisfactory evidence can be provided to the Engineer that thoroughly mixed and uniform concrete is being produced with the proposed mix time. Performance of the plant must conform to the requirements of Table A1.1, of ASTM C 94, Standard Specification for Ready Mixed Concrete. Five of the six tests listed in Table A1.1 must be within the limits of the specification to indicate that uniform concrete is being produced.

If the concrete is mixed in a truck mixer, mix the batch at least 70 revolutions, but not more than 100 revolutions of the drum or blades at mixing speed. After the mixing is completed, set the truck mixer drum at agitating speed. Unless the mixing unit is equipped with an accurate and dependable device that will indicate and control the number of revolutions at mixing speed, perform the mixing at the batch plant and operate the mixing unit at agitating speed while traveling from the plant to the work site. Do not exceed 350 total revolutions (mixing and agitating).

If a truck mixer or truck agitator is used to transport concrete that was completely mixed in a stationary central mixer, agitate the concrete while transporting at the agitating speed specified by the manufacturer of the equipment (shown on the manufacturer's plate on the equipment). Do not exceed 250 total revolutions (additional re-mixing and agitating).

Provide a time slip, for each batch of concrete delivered at the work site, issued at the batching plant that bears the time of charging of the mixer drum with cement and aggregates. On paving projects and other high volume work, the Engineer will determine the haul time and thereafter make random checks, and tickets for every load are not required.

If non-agitating equipment is used for transportation of concrete, provide approved covers for protection against the weather when required by the Engineer.

Place non-agitated concrete within 30 minutes of adding the cement to the water.

Do not use concrete that has developed its initial set. Regardless of the speed of delivery and placement, the Engineer will suspend the concreting operations until corrective measures are taken if there is evidence that the concrete can not be adequately consolidated.

Adding water to concrete after the initial mixing is prohibited, with this exception:

If the concrete is delivered to the work site in a truck mixer, the Engineer will allow water [up to 2 gallons per cubic yard (10 L/cu m) (16 pounds per cubic yard) (9.6 kg/cu m)] be withheld from the mixture at the batch site, and if needed, added at the work site to adjust the slump to comply with the specified requirements. Determine the need for additional water as soon as the load arrives at the construction site. Use a calibrated water-measuring device to add the water, and add the water to the entire load. Do not add more water than was withheld at the batch site. After the additional water is added, turn the drum or blades an additional 20 to 30 revolutions at mixing speed. The Engineer will supervise the adding of water to the load, and will allow this procedure only once per load. See also subsection 402.3e(2).

b. Placement Limitations

(1) Concrete Temperature. Unless otherwise authorized, the temperature of the mixed concrete immediately before placement must be at least 55°F (13ºC), but not more than 70°F (21ºC). With approval by the Engineer, the temperature of the concrete may be adjusted 5°F (3ºC) above or below this range.

(2) Qualification Batch. For Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete, qualify a field batch (one truckload or at least 6 cubic yards (5 cu m))

at least 35 days prior to commencement of placement of the bridge decks. Produce the qualification batch from the same plant that will supply the job concrete. Haul time to the jobsite should be simulated prior to discharge of the concrete for testing. Prior to placing concrete in the qualification slab and on the job, submit documentation to the Engineer verifying that the qualification batch concrete meets the requirements for air content, slump, temperature of plastic concrete, compressive strength, unit weight, and other testing as required by the Engineer.

Before the concrete mixture with plasticizing admixture is used on the project, determine the air content of the qualification batch. Monitor the slump, air content, temperature, and workability at initial batching and estimated time of concrete placement. If these properties are not adequate, repeat the qualification batch until it can be demonstrated that the mix is within acceptable limits as specified in this document.

(3) Placing Concrete at Night. Do not mix, place or finish concrete without sufficient natural light, unless an adequate and artificial lighting system approved by the Engineer is provided.

(4) Placing Concrete in Cold Weather. Unless authorized otherwise by the Engineer, discontinue mixing and concreting operations when the descending ambient air temperature reaches 40°F (4ºC), and do not resume until an ascending ambient air temperature reaches 35°F (2ºC).

If the Engineer permits placing concrete during cold weather, aggregates may be heated by either steam or dry heat before placing them in the mixer. Use an apparatus that heats the weight uniformly and is so arranged as to preclude the possible occurrence of overheated areas which might injure the materials. Do not heat aggregates directly by gas or oil flame or on sheet metal over fire. Aggregates that are heated in bins, by steam-coil or water-coil heating, or by other methods not detrimental to the aggregates may be used. The use of live steam on or through binned aggregates is not permitted. Unless otherwise authorized, the temperature of the mixed concrete must be at least 55°F (13ºC), but not more than 70°F (21ºC) at the time of placing it in the forms. With approval by the engineer, the temperature of the concrete may be up to 5°F (3ºC) below or above this range. Do not place concrete when there is a probability of air temperatures being more than 25°F (14°C) below the temperature of the concrete during the first 24 hours after placement unless insulation is provided for both the deck and the girders. Do not, under any circumstances, continue concrete operations if the ambient air temperature is less than 20°F (-7ºC).

If the ambient air temperature is 35°F (2ºC) or less at the time the concrete is placed, the Engineer may require that the water and the aggregates be heated to at least 70°F (21ºC), but not more than 120°F (49ºC).

Do not place concrete on frozen subgrade or use frozen aggregates in the concrete.

(5) Placing Concrete in Hot Weather. When the ambient temperature is above 90^{o}F (32°C), cool the forms, reinforcing steel, steel beam flanges, and other surfaces which will come in contact with the mix to below 90^{o}F (32°C) by means of a water

spray or other approved methods. For Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete, cool the concrete mixture to maintain the temperature immediately before placement between 55°F (13ºC) and 70°F (21ºC). With approval by the engineer, the temperature of the concrete may be up to 5°F (3ºC) below or above this range.

The temperature of the concrete at time of placement shall be maintained within the specified temperature range by any combination of the following:

- Shading the materials storage areas or the production equipment.
- Cooling the aggregates by sprinkling with potable water.
- Cooling the aggregates or water by refrigeration or replacing a portion or all of the mix water with ice that is flaked or crushed to the extent that the ice will completely melt during mixing of the concrete.
- Liquid nitrogen injection.

402.6 INSPECTION AND TESTING.

Obtain samples of fresh concrete for the determination of slump, temperature, weight per cubic yard (meter), and percent of air from the site the concrete is placed.

The Engineer will cast, store, and test strength test specimens in sets of 5. See requirements in **Table 402-3**.

KDOT will conduct the sampling and test the samples according to **Section 2500** and **Table 402-3**. The Contractor may be directed by the Engineer to assist KDOT in obtaining the fresh concrete samples during the placement operation.

Test the first truckload at truck discharge. Test that load and subsequent loads at the point of deposit on the bridge deck. If potential problems are apparent at the discharge of any truck, test concrete at truck discharge prior to deposit on the bridge deck.

TABLE 402-3, Sampling and Testing Frequency Chart

Tests Required (Record to)	Test Method	CMS	Verification Samples and Tests	Acceptance Samples and Tests
Slump (0.25 inch or 5 mm)	KT-21	a	Each of first 3 truckloads for any individual placement, then 1 of every 2 truckloads	
Temperature (1°F or 0.5°C)	KT-17	a	Every truckload, measured at the truck discharge, and from each sample made for slump determination.	
Mass (0.1 lb or 50 g)	KT-20	a	Every 4 truckloads	
Air Content (0.25%)	KT-18 or KT-19	a	Each of first 3 truckloads for any individual placement, then 1 of every 4 truckloads	
Cylinders (1 lbf or 1 N; 0.1 in or 1 mm; 1 psi or 0.01 MPa)	KT-22 and AASHTO T 22	VER	Make at least two groups of five cylinders per pour or major mix design change with concrete sampled from at least two different truckloads evenly spaced throughout the pour. Include in each group three test cylinders to be cured according to KT-22 and two test cylinders to be field-cured. Store the field-cured cylinders on or adjacent to the bridge. Protect all surfaces of the cylinders from the elements in as near as possible the same way as the deck concrete. Test the field-cured cylinders at the same age as the standard-cured cylinders.	
Density of Fresh Concrete (0.1 lb/cu ft (1 kg/cu m) or 0.1% of optimum density)	KT-36	ACI		b,c: 1 per 150 cu yd (150 cu m) for thin overlays and bridge deck surfacing.

Note a: "Type Insp" must = "ACC" when the assignment of a pay quantity is being made. "ACI" when recording test values for additional acceptance information.
Note b: Normal operation. Minimum frequency for exceptional conditions may be reduced by the District Materials Engineer on a project basis, written justification shall be made to the Chief of the Bureau of Materials and Research and placed in the project documents. (Multi-Level Frequency Chart (see page 17, Appendix A of Construction Manual, Part V).
Note c: Applicable only when specifications contain those requirements.

The Engineer will reject concrete that does not comply with specified requirements.

The Engineer will permit occasional deviations below the specified cement content, if it is due to the air content of the concrete exceeding the designated air content, but only up to the plus 1.0 percent tolerance in the air content. Continuous operation below the specified cement content for any reason is not permitted.

As the work progresses, the Engineer reserves the right to require the Contractor to change the proportions if conditions warrant such changes to produce a satisfactory mix. Any such changes may be made within the limits of the Specifications at no additional compensation to the Contractor.

10-26-06 M&R (REK)

PCC000078 ACCP	Conc (MA) Grade 3.5 (24) (AE) (LC-HPC)	cu yd	(cu m)	90M-7275
PCC000079 ACCP	Conc (CF) Grade 3.5 (24) (AE) (LC-HPC)	cu yd	(cu m)	90M-7275

5095

KANSAS DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION TO THE
STANDARD SPECIFICATIONS 1990 EDITION

NOTE: This special provision is generally written in the imperative mood. The subject, "the *Contractor*" is implied. Also implied in this language are "*shall*", "*shall be*", or similar words and phrases. The word "*will*" generally pertains to decisions or actions` of the Kansas Department of Transportation.

Section 402. Delete the Section and replace with this:

SECTION 402

LOW CRACKING HIGH PERFORMANCE - CONCRETE

402.1 DESCRIPTION

Provide the grades of concrete specified in the Contract Documents.

402.2 MATERIALS

Coarse, fine, and mixed aggregates ....Special Provision 90M-7359
Admixtures ....Section 1400
Cement ....Special Provision 90M/P-212 (latest revision)
Water..Section 2400

402.3 CONCRETE MIX DESIGN

a. General. The Contractor (or a prospective bidder) may contact the District Materials Engineer or the Bureau of Materials and Research for any available information to help determine approximate proportions which will produce concrete having the required characteristics.

The Contractor is responsible for the actual proportions of the concrete mix. If the Contractor requests (in writing), the Engineer will assist in the design of the concrete mix. A copy of the final design is to be submitted to the District Materials Engineer and Bureau of Materials and Research.

Design the concrete mixes specified in the Contract Documents. Design concrete mixes that comply with these requirements:

b. Air-Entrained Concrete for Bridge Decks. Design air-entrained concrete for structures according to these requirements:

TABLE 402-1, Air-Entrained Concrete for Bridge Decks

Grade of Concrete Type of Aggregate (Section 1100)	lb. (kg) of Cement per cu yd (cu m) of Concrete, min/max	lb (kg) of Water per lb (kg) of Cement, max*	Designated Air Content Percent by Volume**
Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC))			
MA-4	500 (300)/ 535(317)	0.42	8.0 ± 1.0

*Maximum limit of lb. (kg) of water per lb. (kg) of cement includes free water in aggregates, but excludes water of absorption of the aggregates.
** Concrete with an air content less than 6.5% or greater than 9.5% shall be rejected.

c. Portland Cement. Select the type of portland cement specified in the Contract Documents. No mineral admixtures are permitted for Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete.

d. Design Air Content. Use the middle of the specified air content range for the design of air-entrained concrete.

e. Admixtures for Air-Entrainment and Water Reduction. Use the dosages recommended by the admixture manufacturers to determine the quantity of each admixture for the concrete mix design. Incorporate and mix the admixtures into the concrete mixtures according to the manufacturer's recommendations.

No set retarding or accelerating admixtures are permitted for use in Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete. These include Type B, C, D, E, and G chemical admixtures as defined by ASTM C 494/C 494M – 05a.

Admixtures containing chloride ion (CL) in excess of 0.1 percent by mass of the admixture shall not be used in Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete.

(1) Air-Entraining Admixture. If specified, use an air-entraining admixture in the concrete mixture. If another admixture is added to an air-entrained concrete mixture, determine if it is necessary to adjust the air-entraining admixture dosage to maintain the specified air content. Use only a vinsol resin or tall oil based air-entraining admixture.

(2) Water-Reducing Admixture. Use a Type A water reducer or a Type F high-range water reducer when necessary to ensure compliance with the specified fresh and hardened concrete properties.

Include a batching sequence in the concrete mix design. Consider the location of the concrete plant in relation to the job site, and identify the approximate quantity, when and at what location the water-reducing admixture is added to the concrete mixture.

Manufacturer may recommend mixing revolutions beyond the limits specified in **subsection 402.5**. If necessary and with the approval of the Engineer, address the additional mixing revolutions (the Engineer will allow up to 60 additional revolutions) in the concrete mix design.

Slump control may be accomplished in the field by redosing. If time and temperature limits are not exceeded, and if at least 30 mixing revolutions remain, the Engineer will allow redosing with up to 50 percent of the original dose. For additional slump control measures see subsection 402.5a.

(3) Adjust the mix designs during the course of the work when necessary to ensure compliance with the specified fresh and hardened concrete properties. Only permit such modifications after trial batches to demonstrate that the adjusted mix design will result in concrete that complies with the specified concrete properties.

The Engineer will allow adjustments to the dose rate of air entraining and water-reducing chemical admixtures to compensate for environmental changes during placement without a new concrete mix design or qualification batch.

f. Designated Slump. Designate a slump for each concrete mix design that is within these limits:

TABLE 402-2, Designated Slump

Type of Work:	Designated Slump inch (mm)	Maximum Allowable Slump inch (mm)
Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC))	1 ½ - 3 (36-75)	4 (100)

NOTE: When high range water reducing admixtures are used with Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete mixtures, **Table 402-2** slump limits shall not be exceeded.

g. Approval of Concrete Mix Designs. Submit all concrete mix designs to the Engineer and the Research Development Engineer for review and approval. Submit completed volumetric mix designs on KDOT Form No. 694 (or other forms approved by the District Materials Engineer).

Do not place any concrete on the Project until the Engineer approves the concrete mix designs, qualification batch, and qualification slab. Once the Engineer approves the concrete mix design, do not make changes without the Engineer's approval (see Section 402.5b).

402.4 REQUIREMENTS FOR COMBINED MATERIALS.

a. Measurements for Proportioning Materials.

(1) Cement. Measure bulk cement by weight. The measurement must be accurate to within 0.5 percent throughout the range of use.

(2) Water. Measure the mixing water by weight or by volume. In either case the measurement must be accurate to within 1 percent throughout the range of use.

(3) Aggregates. Measure the aggregates by weight. The measurement must be accurate to within 0.5 percent throughout the range of use.

(4) Admixtures. Measure liquid admixtures by weight or volume. If liquid admixtures are used in small quantities in proportion to the cement as in the case of air-entraining agents, use readily adjustable mechanical dispensing equipment capable of being set to deliver the required quantity and to cut off the flow automatically when this quantity is discharged. The measurement must be accurate to within 3 percent of the quantity required.

b. Testing of Aggregates. Testing Aggregates at the Batch Site. Provide the Engineer with reasonable facilities at the batch site for obtaining samples of the aggregates. Provide adequate and safe laboratory facilities at the batch site that will allow the Engineer to test the aggregates for compliance with the specified requirements.

KDOT will sample and test aggregates from each source to determine their compliance with specifications. Batching of the concrete mixture is not permitted until the Engineer has determined that the aggregates comply with the specifications. KDOT will conduct the sampling at the batching site, and test the samples according to the Frequency Testing Chart in Part V of the KDOT Construction Manual. For QC/QA Contracts, the Contractor will determine testing intervals within the specified minimum frequency.

After initial testing is complete and the Engineer has determined that the aggregate process control is satisfactory, use the aggregates concurrently with sampling and testing as long as tests indicate compliance with specifications. During the batching operations, sample the aggregates as near the point of batching as feasible. Sample from the stream as the storage bins or weigh hoppers are loaded. If samples cannot be reasonably taken from the stream, take them from approved stockpiles. If test results indicate that an aggregate does not comply with specifications, cease concrete production using that aggregate. Unless a tested and approved stockpile for that aggregate is available at the batch plant, do not use any additional aggregate from that source and specified grading until subsequent sampling and testing of that aggregate indicate compliance with specifications. When tests are completed and the Engineer is satisfied that process control is again adequate, production of concrete using aggregates sampled and tested concurrently with production may resume.

c. Handling of Materials.

(1) Aggregate Stockpiles. Approved stockpiles are permitted only at the batch plant and only for small concrete placements or for the purpose of maintaining concrete production. Mark the approved stockpile with an “Approved Materials” sign. Provide a suitable stockpile area at the batch plant so that aggregates are stored without detrimental segregation or contamination. Unless otherwise approved by the Engineer, no more than 250 tons (Mg) of coarse aggregate and no more than 250 tons (Mg) of fine aggregate tested and approved by the Engineer may be stockpiled at the plant. If mixed aggregate is used, limit the approved stockpile to 500 tons (Mg), the size of each being proportional to the amount of each aggregate to be used in the mix.

Load aggregates into the mixer in such a manner that no material foreign to the concrete or material capable of changing the desired proportions is included. In the event 2 or more sizes or types of coarse or fine aggregates are used on the same project, only 1 size or type of each aggregate may be used on 1 continuous concrete placement.

(2) Segregation. Do not use segregated aggregates until they are thoroughly re-mixed and the resultant pile is of uniform and acceptable grading at any point from which a representative sample is taken.

(3) Cement. Protect cement in storage or stockpiled on the site from any damage by climatic conditions which would change the characteristics or usability of the material.

(4) Moisture. If the moisture content of an approved aggregate remains constant within a tolerance of 0.5 percent plus or minus from the average of that day, they may be used. However, if the moisture content in the aggregate varies by more than the above tolerance, then take whatever corrective measures are necessary to bring the moisture to a constant and uniform quantity before any more concrete is placed. This may be accomplished by handling or manipulating the stockpiles to reduce the moisture content or by adding moisture to the stockpiles in a manner that will produce a uniform moisture content through all portions of the stockpile.

If plant equipment includes an approved accurate moisture-determining device which will make possible the determination of the free moisture in the aggregates and provisions are made for batch to batch correction of the amount of water and the weight of aggregates added, the above requirements relative to handling or manipulating the stockpiles for moisture control will be waived. However, any procedure used will not relieve the producer of the responsibility for delivery of concrete of uniform slump within the limits specified.

Do not use aggregate in the form of frozen lumps in the manufacture of concrete.

(5) Separation of Materials in Tested and Approved Stockpiles. Only use KDOT Approved Materials. Provide separate means for storing materials approved by KDOT. If the producer elects to use KDOT Approved Materials for other work for his own convenience, during the progress of a project requiring KDOT Approved Materials, he must so inform the Engineer and agree to pay all costs of having the additional materials tested.

Clean all conveyors, bins and hoppers of unapproved materials before starting to manufacture concrete for the work.

402.5 MIXING, DELIVERY, AND PLACEMENT LIMITATIONS.

a. Concrete Batching, Mixing, and Delivery. Batch and mix the concrete in a central-mix plant, in a truck mixer, or in a drum mixer at the work site. Provide plant capacity and delivery capacity sufficient to insure continuous delivery at the rate required. The rate of delivery of concrete during concreting operations must provide for the proper handling, placing and finishing of the concrete.

The Engineer must approve the concrete plant/batch site before any concrete is produced for the project. The Engineer will inspect and review the equipment, the method of storing and handling of materials, the production procedures, and the transportation and rate of delivery of concrete from the plant to the point of use. The Engineer will grant approval of the concrete plant/batch site based on compliance with the specified requirements. The Engineer may, at any time, rescind permission to use concrete from a previously approved concrete plant/batch site upon failure to comply with the specified requirements.

The mixing drum must be clean before it is charged with the concrete mixture. Charge the batch into the mixing drum so that a portion of the water is in the drum before the aggregates and cement. The flow of water into the drum throughout the batching operation must be uniform, with all of the water in the drum by the end of the first 15 seconds of the mixing cycle. Keep the throat of the drum free of accumulations that restrict the flow of materials into the drum.

Do not exceed the rated capacity (cubic yards (cu m) shown on the manufacturer's plate on the mixer) of the mixer when batching the concrete. However, the Engineer will allow an overload of up to 10 percent above the rated capacity for central-mix plants and drum mixers at the work site, provided the concrete test data for strength, segregation, and uniform consistency are satisfactory, and no concrete is spilled during the mixing cycle.

Operate the mixing drum at the speed specified by the mixer's manufacturer (shown on the manufacturer's plate on the mixer).

Mixing time is measured from the time all materials, except water, are in the drum. If it is necessary to increase the mixing time to obtain the specified percent of air in air-entrained concrete, the Engineer will determine the mixing time.

If the concrete is mixed in a central-mix plant or a drum mixer at the work site, mix the batch at least 60 seconds, but not more than 5 minutes at mixing speed, with the total mixing revolutions not exceeding 60 revolutions. Mixing time begins after all materials, except water, are in the drum, and ends when the discharge chute opens. Transfer time in multiple drum mixers is included in mixing time. Mix time may be reduced for plants utilizing high performance mixing drums provided satisfactory evidence can be provided to the Engineer that thoroughly mixed and uniform concrete is being produced with the proposed mix time. Performance of the plant must conform to the requirements of Table A1.1, of ASTM C 94, Standard Specification for Ready Mixed Concrete. Five of the six tests listed in Table A1.1 must be within the limits of the specification to indicate that uniform concrete is being produced.

If the concrete is mixed in a truck mixer, mix the batch at least 70 revolutions, but not more than 100 revolutions of the drum or blades at mixing speed. After the mixing is completed, set the truck mixer drum at agitating speed. Unless the mixing unit is equipped with an accurate and dependable device that will indicate and control the number of revolutions at mixing speed, perform the mixing at the batch plant and operate the mixing unit at agitating speed while traveling from the plant to the work site. Do not exceed 350 total revolutions (mixing and agitating).

If a truck mixer or truck agitator is used to transport concrete that was completely mixed in a stationary central mixer, agitate the concrete while transporting at the agitating speed specified by the manufacturer of the equipment (shown on the manufacturer's plate on the equipment). Do not exceed 250 total revolutions (additional re-mixing and agitating).

Provide a time slip, for each batch of concrete delivered at the work site, issued at the batching plant that bears the time of charging of the mixer drum with cement and aggregates. On paving projects and other high volume work, the Engineer will determine the haul time and thereafter make random checks, and tickets for every load are not required.

If non-agitating equipment is used for transportation of concrete, provide approved covers for protection against the weather when required by the Engineer.

Place non-agitated concrete within 30 minutes of adding the cement to the water.

Do not use concrete that has developed its initial set. Regardless of the speed of delivery and placement, the Engineer will suspend the concreting operations until corrective measures are taken if there is evidence that the concrete can not be adequately consolidated.

Adding water to concrete after the initial mixing is prohibited, with this exception:

If the concrete is delivered to the work site in a truck mixer, the Engineer will allow water [up to 2 gallons per cubic yard (10 L/cu m) (16 pounds per cubic yard) (9.6 kg/cu m)] be withheld from the mixture at the batch site, and if needed, added at the work site to adjust the slump to comply with the specified requirements. Determine the need for additional water as soon as the load arrives at the construction site. Use a calibrated water-measuring device to add the water, and add the water to the entire load. Do not add more water than was withheld at the batch site. After the additional water is added, turn the drum or blades an additional 20 to 30 revolutions at mixing speed. The Engineer will supervise the adding of water to the load, and will allow this procedure only once per load. See also subsection 402.3e(2).

b. Placement Limitations

(1) Concrete Temperature. Unless otherwise authorized, the temperature of the mixed concrete immediately before placement must be at least 55°F (13ºC), but not more than 70°F (21ºC). With approval by the Engineer, the temperature of the concrete may be adjusted 5°F (3ºC) above or below this range.

(2) Qualification Batch. For Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete, qualify a field batch (one truckload or at least 6 cubic yards (5 cu m))

at least 35 days prior to commencement of placement of the bridge decks. Produce the qualification batch from the same plant that will supply the job concrete. Haul time to the jobsite should be simulated prior to discharge of the concrete for testing. Prior to placing concrete in the qualification slab and on the job, submit documentation to the Engineer verifying that the qualification batch concrete meets the requirements for air content, slump, temperature of plastic concrete, compressive strength, unit weight, and other testing as required by the Engineer.

Before the concrete mixture with plasticizing admixture is used on the project, determine the air content of the qualification batch. Monitor the slump, air content, temperature, and workability at initial batching and estimated time of concrete placement. If these properties are not adequate, repeat the qualification batch until it can be demonstrated that the mix is within acceptable limits as specified in this document.

(3) Placing Concrete at Night. Do not mix, place or finish concrete without sufficient natural light, unless an adequate and artificial lighting system approved by the Engineer is provided.

(4) Placing Concrete in Cold Weather. Unless authorized otherwise by the Engineer, discontinue mixing and concreting operations when the descending ambient air temperature reaches 40°F (4ºC), and do not resume until an ascending ambient air temperature reaches 35°F (2ºC).

If the Engineer permits placing concrete during cold weather, aggregates may be heated by either steam or dry heat before placing them in the mixer. Use an apparatus that heats the weight uniformly and is so arranged as to preclude the possible occurrence of overheated areas which might injure the materials. Do not heat aggregates directly by gas or oil flame or on sheet metal over fire. Aggregates that are heated in bins, by steam-coil or water-coil heating, or by other methods not detrimental to the aggregates may be used. The use of live steam on or through binned aggregates is not permitted. Unless otherwise authorized, the temperature of the mixed concrete must be at least 55°F (13ºC), but not more than 70°F (21ºC) at the time of placing it in the forms. With approval by the engineer, the temperature of the concrete may be up to 5°F (3ºC) below or above this range. Do not place concrete when there is a probability of air temperatures being more than 25°F (14°C) below the temperature of the concrete during the first 24 hours after placement unless insulation is provided for both the deck and the girders. Do not, under any circumstances, continue concrete operations if the ambient air temperature is less than 20°F (-7ºC).

If the ambient air temperature is 35°F (2ºC) or less at the time the concrete is placed, the Engineer may require that the water and the aggregates be heated to at least 70°F (21ºC), but not more than 120°F (49ºC).

Do not place concrete on frozen subgrade or use frozen aggregates in the concrete.

(5) Placing Concrete in Hot Weather. When the ambient temperature is above 90°F (32°C), cool the forms, reinforcing steel, steel beam flanges, and other surfaces which will come in contact with the mix to below 90°F (32°C) by means of a water

spray or other approved methods. For Grade 3.5 (AE) (LC-HPC) (Grade 24 (AE) (LC-HPC)) concrete, cool the concrete mixture to maintain the temperature immediately before placement between 55°F (13ºC) and 70°F (21ºC). With approval by the engineer, the temperature of the concrete may be up to 5°F (3ºC) below or above this range.

The temperature of the concrete at time of placement shall be maintained within the specified temperature range by any combination of the following:

- Shading the materials storage areas or the production equipment.
- Cooling the aggregates by sprinkling with potable water.
- Cooling the aggregates or water by refrigeration or replacing a portion or all of the mix water with ice that is flaked or crushed to the extent that the ice will completely melt during mixing of the concrete.
- Liquid nitrogen injection.

402.6 INSPECTION AND TESTING.

Obtain samples of fresh concrete for the determination of slump, temperature, weight per cubic yard (meter), and percent of air from the site the concrete is placed.

The Engineer will cast, store, and test strength test specimens in sets of 5. See requirements in **Table 402-3**.

KDOT will conduct the sampling and test the samples according to **Section 2500** and **Table 402-3**. The Contractor may be directed by the Engineer to assist KDOT in obtaining the fresh concrete samples during the placement operation.

Test the first truckload at truck discharge. Test that load and subsequent loads at the point of deposit on the bridge deck. If potential problems are apparent at the discharge of any truck, test concrete at truck discharge prior to deposit on the bridge deck.

TABLE 402-3, Sampling and Testing Frequency Chart

Tests Required (Record to)	Test Method	CMS	Verification Samples and Tests	Acceptance Samples and Tests
Slump (0.25 inch or 5 mm)	KT-21	a	Each of first 3 truckloads for any individual placement, then 1 of every 2 truckloads	
Temperature (1°F or 0.5°C)	KT-17	a	Every truckload, measured at the truck discharge, and from each sample made for slump determination.	
Mass (0.1 lb or 50 g)	KT-20	a	Every 4 truckloads	
Air Content (0.25%)	KT-18 or KT-19	a	Each of first 3 truckloads for any individual placement, then 1 of every 4 truckloads	
Cylinders (1 lbf or 1 N; 0.1 in or 1 mm; 1 psi or 0.01 MPa)	KT-22 and AASHTO T 22	VER	Make at least two groups of five cylinders per pour or major mix design change with concrete sampled from at least two different truckloads evenly spaced throughout the pour. Include in each group three test cylinders to be cured according to KT-22 and two test cylinders to be field-cured. Store the field-cured cylinders on or adjacent to the bridge. Protect all surfaces of the cylinders from the elements in as near as possible the same way as the deck concrete. Test the field-cured cylinders at the same age as the standard-cured cylinders.	
Density of Fresh Concrete (0.1 lb/cu ft (1 kg/cu m) or 0.1% of optimum density)	KT-36	ACI		b,c: 1 per 150 cu yd (150 cu m) for thin overlays and bridge deck surfacing.

Note a: "Type Insp" must = "ACC" when the assignment of a pay quantity is being made. "ACI" when recording test values for additional acceptance information.
Note b: Normal operation. Minimum frequency for exceptional conditions may be reduced by the District Materials Engineer on a project basis, written justification shall be made to the Chief of the Bureau of Materials and Research and placed in the project documents. (Multi-Level Frequency Chart (see page 17, Appendix A of Construction Manual, Part V).
Note c: Applicable only when specifications contain those requirements.

The Engineer will reject concrete that does not comply with specified requirements.

The Engineer will permit occasional deviations below the specified cement content, if it is due to the air content of the concrete exceeding the designated air content, but only up to the plus 1.0 percent tolerance in the air content. Continuous operation below the specified cement content for any reason is not permitted.

As the work progresses, the Engineer reserves the right to require the Contractor to change the proportions if conditions warrant such changes to produce a satisfactory mix. Any such changes may be made within the limits of the Specifications at no additional compensation to the Contractor.

10-26-06 M&R (REK)

PCC000078 ACCP	Conc (MA) Grade 3.5 (24) (AE) (LC-HPC)	cu yd	(cu m)	90M-7275
PCC000079 ACCP	Conc (CF) Grade 3.5 (24) (AE) (LC-HPC)	cu yd	(cu m)	90M-7275

7360

LOW CRACKING HIGH PERFORMANCE CONCRETE SPECFICATIONS

NOTE: These specifications are generally written in the imperative mood. The subject, "the *Contractor*" is implied. Also implied in this language are "*shall*", "*shall be*", or similar words and phrases. The word "*will*" generally pertains to decisions or actions of the City of Overland Park. "Section" refers to the referenced section of the KDOT Standard Specificaton and "Special Provision" refers to the referenced KDOT special provision.

LCHPC-1 LOW CRACKING HIGH PERFORMANCE - CONCRETE

LCHPC-1.1 DESCRIPTION

Provide the grades of concrete specified in the Contract Documents.

LCHPC-1.2 MATERIALS

Coarse, fine, and mixed aggregates LCHPC-2
Admixtures ....Section 1400
Cement ....Special Provision 90M/P-212 (latest revision)
Water..Section 2400

LCHPC-1.3 CONCRETE MIX DESIGN

a. General. The Contractor is responsible for the actual proportions of the concrete mix. A copy of the final design is to be submitted to the Engineer.

Design the concrete mixes specified in the Contract Documents. Compressive strength requirement of 4000 psi of the design mix shall be determined in accordance with ACI 318. Design concrete mixes that comply with these requirements:

b. Air-Entrained Concrete for Bridge Decks. Design air-entrained concrete for structures according to these requirements:

TABLE 1 (LCHPC-1), Air-Entrained Concrete for Bridge Decks

Grade of Concrete Type of Aggregate (Section 1100)	lb. (kg) of Cement per cu yd (cu m) of Concrete, min/max	lb (kg) of Water per lb (kg) of Cement, max*	Designated Air Content Percent by Volume**
Grade 4.0 (AE) (LC-HPC)			
MA-4	500 (300)/ 535(317)	0.42	8.0 ± 1.0

*Maximum limit of lb. (kg) of water per lb. (kg) of cement includes free water in aggregates, but excludes water of absorption of the aggregates.

** Concrete with an air content less than 6.5% or greater than 9.5% shall be rejected.

c. Portland Cement . No mineral admixtures are permitted for Grade 4.0 (AE) (LC-HPC). All cements used shall meet the current ASTM C150 requirements for Type II Portland cement.

d. Design Air Content. Use the middle of the specified air content range for the design of air-entrained concrete.

e. Admixtures for Air-Entrainment and Water Reduction. Use the dosages recommended by the admixture manufacturers to determine the quantity of each admixture for the concrete mix design. Incorporate and mix the admixtures into the concrete mixtures according to the manufacturer's recommendations.

No set retarding or accelerating admixtures are permitted for use in Grade 4.0 (AE) (LC-HPC) concrete. These include Type B, C, D, E, and G chemical admixtures as defined by ASTM C 494/C 494M – 05a.

Admixtures containing chloride ion (CL) in excess of 0.1 percent by mass of the admixture shall not be used in Grade 4.0 (AE) (LC-HPC) concrete.

(1) Air-Entraining Admixture. If specified, use an air-entraining admixture in the concrete mixture. If another admixture is added to an air-entrained concrete mixture, determine if it is necessary to adjust the air-entraining admixture dosage to maintain the specified air content. Use only a vinsol resin or tall oil based air-entraining admixture.

(2) Water-Reducing Admixture. Use a Type A water reducer or a Type F high-range water reducer when necessary to ensure compliance with the specified fresh and hardened concrete properties.

Include a batching sequence in the concrete mix design. Consider the location of the concrete plant in relation to the job site, and identify the approximate quantity, when and at what location the water-reducing admixture is added to the concrete mixture.

Manufacturer may recommend mixing revolutions beyond the limits specified in **subsection LCHPC-1.5**. If necessary and with the approval of the Engineer, address the additional mixing revolutions (the Engineer will allow up to 60 additional revolutions) in the concrete mix design.

Slump control may be accomplished in the field by redosing. If time and temperature limits are not exceeded, and if at least 30 mixing revolutions remain, the Engineer will allow redosing with up to 50 percent of the original dose. For additional slump control measures see subsection LCHPC-1.5a.

(3) Adjust the mix designs during the course of the work when necessary to ensure compliance with the specified fresh and hardened concrete properties. Only permit such modifications after trial batches to demonstrate that the adjusted mix design will result in concrete that complies with the specified concrete properties.

The Engineer will allow adjustments to the dose rate of air entraining and water-reducing chemical admixtures to compensate for environmental changes during placement without a new concrete mix design or qualification batch.

f. Designated Slump. Designate a slump for each concrete mix design that is within these limits:

TABLE 2 (LCHPC-1), Designated Slump

Type of Work:	**Designated Slump** inch (mm)	**Maximum Allowable Slump** inch (mm)
Grade 4.0 (AE) (LC-HPC)	1 ½ - 3 (36-75)	4 (100)

NOTE: When high range water reducing admixtures are used with Grade 4.0 (AE) (LC-HPC) concrete mixtures, **Table 2 (LCHPC-1)** slump limits shall not be exceeded.

g. Approval of Concrete Mix Designs. Submit all concrete mix designs to the Engineer for review and approval. Submit completed volumetric mix designs on KDOT Form No. 694 (or other forms approved by the Engineer).

Do not place any concrete on the Project until the Engineer approves the concrete mix designs, qualification batch, and qualification slab. Once the Engineer approves the concrete mix design, do not make changes without the Engineer's approval (see Section LCHPC-1.5b).

LCHPC-1.4 REQUIREMENTS FOR COMBINED MATERIALS.

a. Measurements for Proportioning Materials.

(1) Cement. Measure bulk cement by weight. The measurement must be accurate to within 0.5 percent throughout the range of use.

(2) Water. Measure the mixing water by weight or by volume. In either case the measurement must be accurate to within 1 percent throughout the range of use.

(3) Aggregates. Measure the aggregates by weight. The measurement must be accurate to within 0.5 percent throughout the range of use.

(4) Admixtures. Measure liquid admixtures by weight or volume. If liquid admixtures are used in small quantities in proportion to the cement as in the case of air-entraining agents, use readily adjustable mechanical dispensing equipment capable of being set to deliver the required quantity and to cut off the flow automatically when this quantity is discharged. The measurement must be accurate to within 3 percent of the quantity required.

b. Testing of Aggregates. Testing Aggregates at the Batch Site. Provide the Engineer with reasonable facilities at the batch site for obtaining samples of the aggregates. Provide adequate and safe laboratory facilities at the batch site that will allow the Engineer to test the aggregates for compliance with the specified requirements.

The Engineer will sample and test aggregates from each source to determine their compliance with specifications. Batching of the concrete mixture is not permitted until the Engineer has determined that the aggregates comply with the specifications. The Engineer will conduct the sampling at the batching site, and test the samples according to the Frequency Testing Chart in Part V of the KDOT Construction Manual. For QC/QA Contracts, the Contractor will determine testing intervals within the specified minimum frequency.

After initial testing is complete and the Engineer has determined that the aggregate process control is satisfactory, use the aggregates concurrently with sampling and testing as long as tests indicate compliance with specifications. During the batching operations, sample the aggregates as near the point of batching as feasible. Sample from the stream as the storage bins or weigh hoppers are loaded. If samples cannot be reasonably taken from the stream, take them from approved stockpiles. If test results indicate that an aggregate does not comply with specifications, cease concrete production using that aggregate. Unless a tested and approved stockpile for that aggregate is available at the batch plant, do not use any additional aggregate from that source and specified grading until subsequent sampling and testing of that aggregate indicate compliance with specifications. When tests are completed and the Engineer is satisfied that process control is again adequate, production of concrete using aggregates sampled and tested concurrently with production may resume.

c. Handling of Materials.

(1) Aggregate Stockpiles. Approved stockpiles are permitted only at the batch plant and only for small concrete placements or for the purpose of maintaining concrete production. Mark the approved stockpile with an "Approved Materials" sign. Provide a suitable stockpile area at

the batch plant so that aggregates are stored without detrimental segregation or contamination. Unless otherwise approved by the Engineer, no more than 250 tons (Mg) of coarse aggregate and no more than 250 tons (Mg) of fine aggregate tested and approved by the Engineer may be stockpiled at the plant. If mixed aggregate is used, limit the approved stockpile to 500 tons (Mg), the size of each being proportional to the amount of each aggregate to be used in the mix.

Load aggregates into the mixer in such a manner that no material foreign to the concrete or material capable of changing the desired proportions is included. In the event 2 or more sizes or types of coarse or fine aggregates are used on the same project, only 1 size or type of each aggregate may be used on 1 continuous concrete placement.

(2) Segregation. Do not use segregated aggregates until they are thoroughly re-mixed and the resultant pile is of uniform and acceptable grading at any point from which a representative sample is taken.

(3) Cement. Protect cement in storage or stockpiled on the site from any damage by climatic conditions which would change the characteristics or usability of the material.

(4) Moisture. If the moisture content of an approved aggregate remains constant within a tolerance of 0.5 percent plus or minus from the average of that day, they may be used. However, if the moisture content in the aggregate varies by more than the above tolerance, then take whatever corrective measures are necessary to bring the moisture to a constant and uniform quantity before any more concrete is placed. This may be accomplished by handling or manipulating the stockpiles to reduce the moisture content or by adding moisture to the stockpiles in a manner that will produce a uniform moisture content through all portions of the stockpile.

If plant equipment includes an approved accurate moisture-determining device which will make possible the determination of the free moisture in the aggregates and provisions are made for batch to batch correction of the amount of water and the weight of aggregates added, the above requirements relative to handling or manipulating the stockpiles for moisture control will be waived. However, any procedure used will not relieve the producer of the responsibility for delivery of concrete of uniform slump within the limits specified.

Do not use aggregate in the form of frozen lumps in the manufacture of concrete.

(5) Separation of Materials in Tested and Approved Stockpiles. Use only materials approved by the Engineer. Provide separate means for storing approved materials. Clean all conveyors, bins and hoppers of unapproved materials before starting to manufacture concrete for the work.

LCHPC-1.5 MIXING, DELIVERY, AND PLACEMENT LIMITATIONS.

a. Concrete Batching, Mixing, and Delivery. Batch and mix the concrete in a central-mix plant, in a truck mixer, or in a drum mixer at the work site. Provide plant capacity and delivery capacity sufficient to insure continuous delivery at the rate required. The rate of delivery of concrete during concreting operations must provide for the proper handling, placing and finishing of the concrete.

The Engineer must approve the concrete plant/batch site before any concrete is produced for the project. The Engineer will inspect and review the equipment, the method of storing and handling of materials, the production procedures, and the transportation and rate of delivery of concrete from the plant to the point of use. The Engineer will grant approval of the concrete plant/batch site based on compliance with the specified requirements. The Engineer may, at any time, rescind permission to use concrete from a previously approved concrete plant/batch site upon failure to comply with the specified requirements.

The mixing drum must be clean before it is charged with the concrete mixture. Charge the batch into the mixing drum so that a portion of the water is in the drum before the aggregates and cement. The flow of water into the drum throughout the batching operation must be uniform, with all of the water in the drum by the end of the first 15 seconds of the mixing cycle. Keep the throat of the drum free of accumulations that restrict the flow of materials into the drum.

Do not exceed the rated capacity (cubic yards (cu m) shown on the manufacturer's plate on the mixer) of the mixer when batching the concrete. However, the Engineer will allow an overload of up to 10 percent above the rated capacity for central-mix plants and drum mixers at the work site, provided the concrete test data for strength, segregation, and uniform consistency are satisfactory, and no concrete is spilled during the mixing cycle.

Operate the mixing drum at the speed specified by the mixer's manufacturer (shown on the manufacturer's plate on the mixer).

Mixing time is measured from the time all materials, except water, are in the drum. If it is necessary to increase the mixing time to obtain the specified percent of air in air-entrained concrete, the Engineer will determine the mixing time.

If the concrete is mixed in a central-mix plant or a drum mixer at the work site, mix the batch at least 60 seconds, but not more than 5 minutes at mixing speed, with the total mixing revolutions not exceeding 60 revolutions. Mixing time begins after all materials, except water, are in the drum, and ends when the discharge chute opens. Transfer time in multiple drum mixers is included in mixing time. Mix time may be reduced for plants utilizing high performance mixing drums provided satisfactory evidence can be provided to the Engineer that thoroughly mixed and uniform concrete is being produced with the proposed mix time. Performance of the plant must conform to the requirements of Table A1.1, of ASTM C 94, Standard Specification for Ready Mixed Concrete. Five of the six tests listed in Table A1.1 must be within the limits of the specification to indicate that uniform concrete is being produced.

If the concrete is mixed in a truck mixer, mix the batch at least 70 revolutions, but not more than 100 revolutions of the drum or blades at mixing speed. After the mixing is completed, set the truck mixer drum at agitating speed. Unless the mixing unit is equipped with an accurate and dependable device that will indicate and control the number of revolutions at mixing speed, perform the mixing at the batch plant and operate the mixing unit at agitating speed while traveling from the plant to the work site. Do not exceed 350 total revolutions (mixing and agitating).

If a truck mixer or truck agitator is used to transport concrete that was completely mixed in a stationary central mixer, agitate the concrete while transporting at the agitating speed specified by the manufacturer of the equipment (shown on the manufacturer's plate on the equipment). Do not exceed 250 total revolutions (additional re-mixing and agitating).

Provide a time slip, for each batch of concrete delivered at the work site, issued at the batching plant that bears the time of charging of the mixer drum with cement and aggregates. On paving projects and other high volume work, the Engineer will determine the haul time and thereafter make random checks, and tickets for every load are not required.

If non-agitating equipment is used for transportation of concrete, provide approved covers for protection against the weather when required by the Engineer.

Place non-agitated concrete within 30 minutes of adding the cement to the water.

Do not use concrete that has developed its initial set. Regardless of the speed of delivery and placement, the Engineer will suspend the concreting operations until corrective measures are taken if there is evidence that the concrete can not be adequately consolidated.

Adding water to concrete after the initial mixing is prohibited, with this exception: If the concrete is delivered to the work site in a truck mixer, the Engineer will allow water [up to 2 gallons per cubic yard (10 L/cu m) (16 pounds per cubic yard) (9.6 kg/cu m)] be withheld from the mixture at the batch site, and if needed, added at the work site to adjust the slump to comply with the specified requirements. Determine the need for additional water as soon as the load arrives at the construction site. Use a calibrated water-measuring device to add the water, and add the water to the entire load. Do not add more water than was withheld at the batch site. After the additional water is added, turn the drum or blades an additional 20 to 30 revolutions at mixing speed. The Engineer will supervise the adding of water to the load, and will allow this procedure only once per load. See also subsection LCHPC-1.3e(2).

b. Placement Limitations

(1) Concrete Temperature. Unless otherwise authorized, the temperature of the mixed concrete immediately before placement must be at least 55°F (13°C), but not more than 70°F (21°C). With approval by the Engineer, the temperature of the concrete may be adjusted 5°F (3°C) above or below this range.

(2) Qualification Batch. For Grade 4.0 (AE) (LC-HPC) concrete, qualify a field batch (one truckload or at least 6 cubic yards (5 cu m)) at least 35 days prior to commencement of placement of the bridge decks. Produce the qualification batch from the same plant that will supply the job concrete. Haul time to the jobsite should be simulated prior to discharge of the concrete for testing. Prior to placing concrete in the qualification slab and on the job, submit documentation to the Engineer verifying that the qualification batch concrete meets the requirements for air content, slump, temperature of plastic concrete, compressive strength, unit weight, and other testing as required by the Engineer.

Before the concrete mixture with plasticizing admixture is used on the project, determine the air content of the qualification batch. Monitor the slump, air content, temperature, and workability at initial batching and estimated time of concrete placement. If these properties are not adequate, repeat the qualification batch until it can be demonstrated that the mix is within acceptable limits as specified in this document.

(3) Placing Concrete at Night. Do not mix, place or finish concrete without sufficient natural light, unless an adequate and artificial lighting system approved by the Engineer is provided.

(4) Placing Concrete in Cold Weather. Unless authorized otherwise by the Engineer, discontinue mixing and concreting operations when the descending ambient air temperature reaches 40°F (4°C), and do not resume until an ascending ambient air temperature reaches 35°F (2°C).

If the Engineer permits placing concrete during cold weather, aggregates may be heated by either steam or dry heat before placing them in the mixer. Use an apparatus that heats the weight uniformly and is so arranged as to preclude the possible occurrence of overheated areas which might injure the materials. Do not heat aggregates directly by gas or oil flame or on sheet metal over fire. Aggregates that are heated in bins, by steam-coil or water-coil heating, or by other methods not detrimental to the aggregates may be used. The use of live steam on or through binned aggregates is not permitted. Unless otherwise authorized, the temperature of the mixed concrete must be at least 55°F (13°C), but not more than 70°F (21°C) at the time of placing it in the forms. With approval by the engineer, the temperature of the concrete may be up to 5°F (3°C) below or above this range. Do not place concrete when there is a probability of air temperatures being more than 25°F (14°C) below the temperature of the concrete during the first 24 hours after placement unless insulation is provided for both the deck and the girders. Do not, under any circumstances, continue concrete operations if the ambient air temperature is less than 20°F (-7°C).

If the ambient air temperature is 35°F (2°C) or less at the time the concrete is placed, the Engineer may require that the water and the aggregates be heated to at least 70°F (21°C), but not more than 120°F (49°C).

Do not place concrete on frozen subgrade or use frozen aggregates in the concrete.

(5) Placing Concrete in Hot Weather. When the ambient temperature is above 90°F (32°C), cool the forms, reinforcing steel, steel beam flanges, and other surfaces which will come in contact with the mix to below 90°F (32°C) by means of a water spray or other approved methods. For Grade 4.0 (AE) (LC-HPC) concrete, cool the concrete mixture to maintain the temperature immediately before placement between 55°F (13°C) and 70°F (21°C). With approval by the Engineer, the temperature of the concrete may be up to 5°F (3°C) below or above this range.

The temperature of the concrete at time of placement shall be maintained within the specified temperature range by any combination of the following:

- Shading the materials storage areas or the production equipment.
- Cooling the aggregates by sprinkling with potable water.
- Cooling the aggregates or water by refrigeration or replacing a portion or all of the mix water with ice that is flaked or crushed to the extent that the ice will completely melt during mixing of the concrete.
- Liquid nitrogen injection.

LCHPC-1.6 INSPECTION AND TESTING.

Obtain samples of fresh concrete for the determination of slump, temperature, weight per cubic yard (meter), and percent of air from the site the concrete is placed.

The Engineer will cast, store, and test strength test specimens in sets of 5. See requirements in **Table 3 (LCHPC-1)**.

The Engineer will conduct the sampling and test the samples according to **Section 2500** and **Table 3 (LCHPC-1)**. The Contractor may be directed by the Engineer to assist in obtaining the fresh concrete samples during the placement operation.

Test the first truckload at truck discharge. Test that load and subsequent loads at the point of deposit on the bridge deck. If potential problems are apparent at the discharge of any truck, test concrete at truck discharge prior to deposit on the bridge deck.

TABLE 3 (LCHPC-1), Sampling and Testing Frequency Chart

Tests Required (Record to)	Test Method	CMS	Verification Samples and Tests	Acceptance Samples and Tests
Slump (0.25 inch or 5 mm)	KT-21	a	Each of first 3 truckloads for any individual placement, then 1 of every 2 truckloads	
Temperature (1°F or 0.5°C)	KT-17	a	Every truckload, measured at the truck discharge, and from each sample made for	

Tests Required (Record to)	Test Method	CMS	Verification Samples and Tests	Acceptance Samples and Tests
			slump determination.	
Mass (0.1 lb or 50 g)	KT-20	a	Every 4 truckloads	
Air Content (0.25%)	KT-18 or KT-19	a	Each of first 3 truckloads for any individual placement, then 1 of every 4 truckloads	
Cylinders (1 lbf or 1 N; 0.1 in or 1 mm; 1 psi or 0.01 MPa)	KT-22 and AASHTO T 22	VER	Make at least two groups of five cylinders per pour or major mix design change with concrete sampled from at least two different truckloads evenly spaced throughout the pour. Include in each group three test cylinders to be cured according to KT-22 and two test cylinders to be field-cured. Store the field-cured cylinders on or adjacent to the bridge. Protect all surfaces of the cylinders from the elements in as near as possible the same way as the deck concrete. Test the field-cured cylinders at the same age as the standard-cured cylinders.	
Density of Fresh Concrete (0.1 lb/cu ft (1 kg/cu m) or 0.1% of optimum density)	KT-36	ACI		b,c: 1 per 150 cu yd (150 cu m) for thin overlays and bridge deck surfacing.

Note a: "Type Insp" must = "ACC" when the assignment of a pay quantity is being made. "ACI" when recording test values for additional acceptance information.

Note b: Normal operation. Minimum frequency for exceptional conditions may be reduced by the District Materials Engineer on a project basis, written justification shall be made to the Chief of the Bureau of Materials and Research and placed in the project documents. (Multi-Level Frequency Chart (see page 17, Appendix A of Construction Manual, Part V).

Note c: Applicable only when specifications contain those requirements.

The Engineer will reject concrete that does not comply with specified requirements.

The Engineer will permit occasional deviations below the specified cement content, if it is due to the air content of the concrete exceeding the designated air content, but only up to the plus 1.0 percent tolerance in the air content. Continuous operation below the specified cement content for any reason is not permitted.

As the work progresses, the Engineer reserves the right to require the Contractor to change the proportions if conditions warrant such changes to produce a satisfactory mix. Any such changes may be made within the limits of the Specifications at no additional compensation to the Contractor.

KANSAS DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION TO THE
STANDARD SPECIFICATIONS 2007 EDITION

Add a new SECTION to DIVISION 400:

LOW-CRACKING HIGH-PERFORMANCE CONCRETE

1.0 DESCRIPTION

Provide the grades of low-cracking high-performance concrete (LC-HPC) specified in the Contract Documents.

2.0 MATERIALS

Coarse, Fine & Mixed Aggregate .... **07-PS0165, latest version**
Admixtures .... **DIVISION 1400**
Cement .... **DIVISION 2000**
Water .... **DIVISION 2400**

3.0 CONCRETE MIX DESIGN

a. General. Design the concrete mixes specified in the Contract Documents.

Provide aggregate gradations that comply with **07-PS0165, latest version** and Contract Documents.

If desired, contact the DME for available information to help determine approximate proportions to produce concrete having the required characteristics on the project.

Take full responsibility for the actual proportions of the concrete mix, even if the Engineer assists in the design of the concrete mix.

Submit all concrete mix designs to the Engineer for review and approval. Submit completed volumetric mix designs on KDOT Form No. 694 (or other forms approved by the DME).

Do not place any concrete on the project until the Engineer approves the concrete mix designs. Once the Engineer approves the concrete mix design, do not make changes without the Engineer's approval.

Design concrete mixes that comply with these requirements:

b. Air-Entrained Concrete for Bridge Decks. Design air-entrained concrete for structures according to **TABLE 1-1**.

TABLE 1-1: AIR ENTRAINED CONCRETE FOR BRIDGE DECKS

Grade of Concrete Type of Aggregate (SECTION 1100)	lb of Cementitious per cu yd of Concrete, min/max	lb of Water per lb of Cementitious*	Designated Air Content Percent by Volume**	Specified 28-day Compressive Strength Range, psi
Grade 3.5 (AE) (LC-HPC)				
MA-4	500 / 540	0.44 – 0.45	8.0 ± 1.0	3500 – 5500

*Limits of lb. of water per lb. of cementitious. Includes free water in aggregates, but excludes water of absorption of the aggregates. With approval of the Engineer, may be decreased to 0.43 on-site.
**Concrete with an air content less than 6.5% or greater than 9.5% shall be rejected. The Engineer will sample concrete for tests at the discharge end of the conveyor, bucket or if pumped, the piping.

c. Portland Cement. Select the type of portland cement specified in the Contract Documents. Mineral admixtures are prohibited for Grade 3.5 (AE) (LC-HPC) concrete.

d. Design Air Content. Use the middle of the specified air content range for the design of air-entrained concrete.

e. Admixtures for Air-Entrainment and Water Reduction. Verify that the admixtures used are compatible and will work as intended without detrimental effects. Use the dosages recommended by the admixture manufacturers to determine the quantity of each admixture for the concrete mix design. Incorporate and mix the admixtures into the concrete mixtures according to the manufacturer's recommendations.

Set retarding or accelerating admixtures are prohibited for use in Grade 3.5 (AE) (LC-HPC) concrete. These include Type B, C, D, E, and G chemical admixtures as defined by ASTM C 494/C 494M – 08. Do not use admixtures containing chloride ion (CL) in excess of 0.1 percent by mass of the admixture in Grade 3.5 (AE) (LC-HPC) concrete.

(1) Air-Entraining Admixture. If specified, use an air-entraining admixture in the concrete mixture. If another admixture is added to an air-entrained concrete mixture, determine if it is necessary to adjust the air-entraining admixture dosage to maintain the specified air content. Use only a vinsol resin or tall oil based air-entraining admixture.

(2) Water-Reducing Admixture. Use a Type A water reducer or a dual rated Type A water reducer – Type F high-range water reducer, when necessary to obtain compliance with the specified fresh and hardened concrete properties.

Include a batching sequence in the concrete mix design. Consider the location of the concrete plant in relation to the job site, and identify the approximate quantity, when and at what location the water-reducing admixture is added to the concrete mixture.

The manufacturer may recommend mixing revolutions beyond the limits specified in **subsection 5.0**. If necessary and with the approval of the Engineer, address the additional mixing revolutions (the Engineer will allow up to 60 additional revolutions) in the concrete mix design.

Slump control may be accomplished in the field only by redosing with a water-reducing admixture. If time and temperature limits are not exceeded, and if at least 30 mixing revolutions remain, the Engineer will allow redosing with up to 50% of the original dose.

(3) Adjust the mix designs during the course of the work when necessary to achieve compliance with the specified fresh and hardened concrete properties. Only permit such modifications after trial batches to demonstrate that the adjusted mix design will result in concrete that complies with the specified concrete properties.

The Engineer will allow adjustments to the dose rate of air entraining and water-reducing chemical admixtures to compensate for environmental changes during placement without a new concrete mix design or qualification batch.

f. Designated Slump. Designate a slump for each concrete mix design within the limits in **TABLE 1-2**.

TABLE 1-2: DESIGNATED SLUMP*

Type of Work	Designated Slump (inches)
Grade 3.5 (AE) (LC-HPC)	1 ½ - 3

* The Engineer will obtain sample concrete at the discharge end of the conveyor, bucket or if pumped, the piping.

If potential problems are apparent at the discharge of any truck, and the concrete is tested at the truck discharge (according to **subsection 6.0**), the Engineer will reject concrete with a slump greater than 3 ½ inches at the truck discharge.

4.0 REQUIREMENTS FOR COMBINED MATERIALS

a. Measurements for Proportioning Materials.

(1) Cement. Measure cement as packed by the manufacturer. A sack of cement is considered as 0.04 cubic yards weighing 94 pounds net. Measure bulk cement by weight. In either case, the measurement must be accurate to within 0.5% throughout the range of use.

(2) Water. Measure the mixing water by weight or volume. In either case, the measurement must be accurate to within 1% throughout the range of use.

(3) Aggregates. Measure the aggregates by weight. The measurement must be accurate to within 0.5% throughout the range of use.

(4) Admixtures. Measure liquid admixtures by weight or volume. If liquid admixtures are used in small quantities in proportion to the cement as in the case of air-entraining agents, use readily adjustable mechanical dispensing equipment

capable of being set to deliver the required quantity and to cut off the flow automatically when this quantity is discharged. The measurement must be accurate to within 3% of the quantity required.

b. Testing of Aggregates. Testing Aggregates at the Batch Site. Provide the Engineer with reasonable facilities at the batch site for obtaining samples of the aggregates. Provide adequate and safe laboratory facilities at the batch site allowing the Engineer to test the aggregates for compliance with the specified requirements.

KDOT will sample and test aggregates from each source to determine their compliance with specifications. Do not batch the concrete mixture until the Engineer has determined that the aggregates comply with the specifications. KDOT will conduct sampling at the batching site, and test samples according to the Sampling and Testing Frequency Chart in Part V. For QC/QA Contracts, establish testing intervals within the specified minimum frequency.

After initial testing is complete and the Engineer has determined that the aggregate process control is satisfactory, use the aggregates concurrently with sampling and testing as long as tests indicate compliance with specifications. When batching, sample the aggregates as near the point of batching as feasible. Sample from the stream as the storage bins or weigh hoppers are loaded. If samples can not be taken from the stream, take them from approved stockpiles, or use a template and sample from the conveyor belt. If test results indicate an aggregate does not comply with specifications, cease concrete production using that aggregate. Unless a tested and approved stockpile for that aggregate is available at the batch plant, do not use any additional aggregate from that source and specified grading until subsequent sampling and testing of that aggregate indicate compliance with specifications. When tests are completed and the Engineer is satisfied that process control is again adequate, production of concrete using aggregates tested concurrently with production may resume.

c. Handling of Materials.

(1) Aggregate Stockpiles. Approved stockpiles are permitted only at the batch plant and only for small concrete placements or for the purpose of maintaining concrete production. Mark the approved stockpile with an “Approved Materials” sign. Provide a suitable stockpile area at the batch plant so that aggregates are stored without detrimental segregation or contamination. At the plant, limit stockpiles of tested and approved coarse aggregate and fine aggregate to 250 tons each, unless approved for more by the Engineer. If mixed aggregate is used, limit the approved stockpile to 500 tons, the size of each being proportional to the amount of each aggregate to be used in the mix.

Load aggregates into the mixer so no material foreign to the concrete or material capable of changing the desired proportions is included. When 2 or more sizes or types of coarse or fine aggregates are used on the same project, only 1 size or type of each aggregate may be used for any one continuous concrete placement.

(2) Segregation. Do not use segregated aggregates. Previously segregated materials may be thoroughly re-mixed and used when representative samples taken anywhere in the stockpile indicated a uniform gradation exists.

(3) Cement. Protect cement in storage or stockpiled on the site from any damage by climatic conditions which would change the characteristics or usability of the material.

(4) Moisture. Provide aggregate with a moisture content of ± 0.5% from the average of that day. If the moisture content in the aggregate varies by more than the above tolerance, take whatever corrective measures are necessary to bring the moisture to a constant and uniform consistency before placing concrete. This may be accomplished by handling or manipulating the stockpiles to reduce the moisture content, or by adding moisture to the stockpiles in a manner producing uniform moisture content through all portions of the stockpile.

For plants equipped with an approved accurate moisture-determining device capable of determining the free moisture in the aggregates, and provisions made for batch to batch correction of the amount of water and the weight of aggregates added, the requirements relative to manipulating the stockpiles for moisture control will be waived. Any procedure used will not relieve the producer of the responsibility for delivery of concrete meeting the specified water-cement ratio and slump requirements.

Do not use aggregate in the form of frozen lumps in the manufacture of concrete.

(5) Separation of Materials in Tested and Approved Stockpiles. Only use KDOT Approved Materials. Provide separate means for storing materials approved by KDOT. If the producer elects to use KDOT Approved Materials for non-KDOT work, during the progress of a project requiring KDOT Approved Materials, inform the Engineer and agree to pay all costs for additional materials testing.

Clean all conveyors, bins and hoppers of unapproved materials before beginning the manufacture of concrete for KDOT work.

5.0 MIXING, DELIVERY, AND PLACEMENT LIMITATIONS

a. Concrete Batching, Mixing, and Delivery. Batch and mix the concrete in a central-mix plant, in a truck mixer, or in a drum mixer at the work site. Provide plant capacity and delivery capacity sufficient to maintain continuous delivery at the rate required. The delivery rate of concrete during concreting operations must provide for the proper handling, placing and finishing of the concrete.

Seek the Engineer’s approval of the concrete plant/batch site before any concrete is produced for the project. The Engineer will inspect the equipment, the method of storing and handling of materials, the production procedures, and the transportation and rate of delivery of concrete from the plant to the point of use. The Engineer will grant approval of the concrete plant/batch site based on compliance with the specified requirements. The Engineer may, at any time, rescind permission to use concrete from a previously approved concrete plant/batch site upon failure to comply with the specified requirements.

Clean the mixing drum before it is charged with the concrete mixture. Charge the batch into the mixing drum so that a portion of the water is in the drum before the aggregates and cementitious. Uniformly flow materials into the drum throughout the batching operation. Add all mixing water in the drum by the end of the first 15 seconds of the mixing cycle. Keep the throat of the drum free of accumulations that restrict the flow of materials into the drum.

Do not exceed the rated capacity (cubic yards shown on the manufacturer's plate on the mixer) of the mixer when batching the concrete. The Engineer will allow an overload of up to 10% above the rated capacity for central-mix plants and drum mixers at the work site, provided the concrete test data for strength, segregation and uniform consistency are satisfactory, and no concrete is spilled during the mixing cycle.

Operate the mixing drum at the speed specified by the mixer's manufacturer (shown on the manufacturer's plate on the mixer).

Mixing time is measured from the time all materials, except water, are in the drum. If it is necessary to increase the mixing time to obtain the specified percent of air in air-entrained concrete, the Engineer will determine the mixing time.

If the concrete is mixed in a central-mix plant or a drum mixer at the work site, mix the batch between 1 to 5 minutes at mixing speed. Do not exceed the maximum total 60 mixing revolutions. Mixing time begins after all materials, except water, are in the drum, and ends when the discharge chute opens. Transfer time in multiple drum mixers is included in mixing time. Mix time may be reduced for plants utilizing high performance mixing drums provided thoroughly mixed and uniform concrete is being produced with the proposed mix time. Performance of the plant must comply with Table A1.1, of ASTM C 94, Standard Specification for Ready Mixed Concrete. Five of the six tests listed in Table A1.1 must be within the limits of the specification to indicate that uniform concrete is being produced.

If the concrete is mixed in a truck mixer, mix the batch between 70 and 100 revolutions of the drum or blades at mixing speed. After the mixing is completed, set the truck mixer drum at agitating speed. Unless the mixing unit is equipped with an accurate device indicating and controlling the number of revolutions at mixing speed, perform the mixing at the batch plant and operate the mixing unit at agitating speed while traveling from the plant to the work site. Do not exceed 350 total revolutions (mixing and agitating).

If a truck mixer or truck agitator is used to transport concrete that was completely mixed in a stationary central mixer, agitate the concrete while transporting at the agitating speed specified by the manufacturer of the equipment (shown on the manufacturer's plate on the equipment). Do not exceed 250 total revolutions (additional re-mixing and agitating).

Provide a batch slip including batch weights of every constituent of the concrete and time for each batch of concrete delivered at the work site, issued at the batching plant that bears the time of charging of the mixer drum with cementitious and aggregates. Include quantities, type, product name and manufacturer of all admixtures on the batch ticket.

If non-agitating equipment is used for transportation of concrete, provide approved covers for protection against the weather when required by the Engineer.

Place non-agitated concrete within 30 minutes of adding the cement to the water.

Do not use concrete that has developed its initial set. Regardless of the speed of delivery and placement, the Engineer will suspend the concreting operations until corrective measures are taken if there is evidence that the concrete can not be adequately consolidated.

Adding water to concrete after the initial mixing is prohibited. Add all water at the plant. If needed, adjust slump through the addition of a water reducer according to **subsection 3.0e.(2)**.

b. Placement Limitations.

(1) Concrete Temperature. Unless otherwise authorized by the Engineer, the temperature of the mixed concrete immediately before placement is a minimum of 55°F, and a maximum of 70°F. With approval by the Engineer, the temperature of the concrete may be adjusted 5°F above or below this range.

(2) Qualification Batch. For Grade 3.5 (AE) (LC-HPC) concrete, qualify a field batch (one truckload or at least 6 cubic yards) at least 35 days prior to commencement of placement of the bridge decks. Produce the qualification batch from the same plant that will supply the job concrete. Simulate haul time to the jobsite prior to discharge of the concrete for testing. Prior to placing concrete in the qualification slab and on the job, submit documentation to the Engineer verifying that the qualification batch concrete meets the requirements for air content, slump, temperature of plastic concrete, compressive strength, unit weight and other testing as required by the Engineer.

Before the concrete mixture with plasticizing admixture is used on the project, determine the air content of the qualification batch. Monitor the slump, air content, temperature and workability at initial batching and estimated time of concrete placement. If these properties are not adequate, repeat the qualification batch until it can be demonstrated that the mix is within acceptable limits as specified in this specification.

(3) Placing Concrete at Night. Do not mix, place or finish concrete without sufficient natural light, unless an adequate and artificial lighting system approved by the Engineer is provided.

(4) Placing Concrete in Cold Weather. Unless authorized otherwise by the Engineer, mixing and concreting operations shall not proceed once the descending ambient air temperature reaches 40°F, and may not be initiated until an ascending

ambient air temperature reaches 40°F. The ascending ambient air temperature for initiating concreting operations shall increase to 45°F if the maximum ambient air temperature is expected to be between 55°F and 60°F during or within 24 hours of placement and to 50°F if the ambient air temperature is expected to equal or exceed 60°F during or within 24 hours of placement.

If the Engineer permits placing concrete during cold weather, aggregates may be heated by either steam or dry heat before placing them in the mixer. Use an apparatus that heats the weight uniformly and is so arranged as to preclude the possible occurrence of overheated areas which might injure the materials. Do not heat aggregates directly by gas or oil flame or on sheet metal over fire. Aggregates that are heated in bins, by steam-coil or water-coil heating, or by other methods not detrimental to the aggregates may be used. The use of live steam on or through binned aggregates is prohibited. Unless otherwise authorized, maintain the temperature of the mixed concrete between 55°F to 70°F at the time of placing it in the forms. With approval by the Engineer, the temperature of the concrete may be adjusted up to 5°F above or below this range. Do not place concrete when there is a probability of air temperatures being more than 25°F below the temperature of the concrete during the first 24 hours after placement unless insulation is provided for both the deck and the girders. Do not, under any circumstances, continue concrete operations if the ambient air temperature is less than 20°F.

If the ambient air temperature is 40°F or less at the time the concrete is placed, the Engineer may permit the water and the aggregates be heated to at least 70°F, but not more than 120°F.

Do not place concrete on frozen subgrade or use frozen aggregates in the concrete.

(5) Placing Concrete in Hot Weather. When the ambient temperature is above 90°F, cool the forms, reinforcing steel, steel beam flanges, and other surfaces which will come in contact with the mix to below 90°F by means of a water spray or other approved methods. For Grade 3.5 (AE) (LC-HPC) concrete, cool the concrete mixture to maintain the temperature immediately before placement between 55°F and 70°F. With approval by the Engineer, the temperature of the concrete may be up to 5°F below or above this range.

Maintain the temperature of the concrete at time of placement within the specified temperature range by any combination of the following:

- Shading the materials storage areas or the production equipment.
- Cooling the aggregates by sprinkling with potable water.
- Cooling the aggregates or water by refrigeration or replacing a portion or all of the mix water with ice that is flaked or crushed to the extent that the ice will completely melt during mixing of the concrete.
- Liquid nitrogen injection.

6.0 INSPECTION AND TESTING

The Engineer will test the first truckload of concrete by obtaining a sample of fresh concrete at truck discharge and by obtaining a sample of fresh concrete at the discharge end of the conveyor, bucket or if pumped, the piping. The Engineer will obtain subsequent sample concrete for tests at the discharge end of the conveyor, bucket or if pumped, the discharge end of the piping. If potential problems are apparent at the discharge of any truck, the Engineer will test the concrete at truck discharge prior to deposit on the bridge deck.

The Engineer will cast, store, and test strength test specimens in sets of 5. See **TABLE 1-3**.

KDOT will conduct the sampling and test the samples according to **SECTION 2500** and **TABLE 1-3**. The Contractor may be directed by the Engineer to assist KDOT in obtaining the fresh concrete samples during the placement operation.

A plan will be finalized prior to the construction date as to how out-of-specification concrete will be handled.

TABLE 1-3: SAMPLING AND TESTING FREQUENCY CHART				
Tests Required (Record to)	**Test Method**	**CMS**	**Verification Samples and Tests**	**Acceptance Samples and Tests**
Slump (0.25 inch)	KT-21	a	Each of first 3 truckloads for any individual placement, then 1 of every 3 truckloads	
Temperature (1°F)	KT-17	a	Every truckload, measured at the truck discharge, and from each sample made for slump determination.	
Mass (0.1 lb)	KT-20	a	One of every 6 truckloads	
Air Content (0.25%)	KT-18 or KT-19	a	Each of first 3 truckloads for any individual placement, then 1 of every 6 truckloads	
Cylinders (1 lbf; 0.1 in; 1 psi)	KT-22 and AASHTO T 22	VER	Make at least 2 groups of 5 cylinders per pour or major mix design change with concrete sampled from at least 2 different truckloads evenly spaced throughout the pour, with a minimum of 1 set for every 100 cu yd. Include in each group 3 test cylinders to be cured according to KT-22 and 2 test cylinders to be field-cured. Store the field-cured cylinders on or adjacent to the bridge. Protect all surfaces of the cylinders from the elements in as near as possible the same way as the deck concrete. Test the field-cured cylinders at the same age as the standard-cured cylinders.	
Density of Fresh Concrete (0.1 lb/cu ft or 0.1% of optimum density)	KT-36	ACI		b,c: 1 per 100 cu yd for thin overlays and bridge deck surfacing.

Note a: "Type Insp" must = "ACC" when the assignment of a pay quantity is being made. "ACI" when recording test values for additional acceptance information.
Note b: Normal operation. Minimum frequency for exceptional conditions may be reduced by the DME on a project basis, written justification shall be made to the Chief of the Bureau of Materials and Research and placed in the project documents. (Multi-Level Frequency Chart (see page 17, Appendix A of Construction Manual, Part V).
Note c: Applicable only when specifications contain those requirements.

The Engineer will reject concrete that does not comply with specified requirements.

The Engineer will permit occasional deviations below the specified cementitious content, if it is due to the air content of the concrete exceeding the designated air content, but only up to the maximum tolerance in the air content. Continuous operation below the specified cement content for any reason is prohibited.

As the work progresses, the Engineer reserves the right to require the Contractor to change the proportions if conditions warrant such changes to produce a satisfactory mix. Any such changes may be made within the limits of the Specifications at no additional compensation to the Contractor.

07-29-09 LAL
PS0166

C.4 CONSTRUCTION

The seven versions of the construction special provisions for Phase 1 construction and the Phase 2 special provisions follow, including: 90M-7190, 90M-7276, 90M-7332, 90M-5097, 90M-7361, LCHPC-3, and 07-LC-HPC-Const. The K7891 Addendum is provided in Section C.2 above. The KDOT special provision 90M-0036 contractor attendance at the pre-bid conference is also provided.

The KDOT standard specifications (1990 and 2007 versions), as well as all of the special provisions for the Control bridge decks, are found online at www.ksdot.org/burConsMain/specprov/specifications.asp.

KANSAS DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION TO THE
STANDARD SPECIFICATIONS, 1990 EDITION

NOTE: This special provision is generally written in the imperative mood. The subject, "the *Contractor*" is implied. Also implied in this language are "*shall*", "*shall be*", or similar words and phrases. The word "*will*" generally pertains to decisions or actions of the Kansas Department of Transportation.

LOW CRACKING – HIGH PERFORMANCE CONCRETE (LC-HPC) CONSTRUCTION

1.0 DESCRIPTION.

Construct the concrete bridge deck designated in the Contract Documents that complies with Section 701 and this Special Provision.

BID ITEMS	**UNIT**
Concrete Grade * (AE)(LC-HPC) * Grade of Concrete	Cubic yard (cu m)
Trial Slab	Cubic yard (cu m)

2.0 MATERIALS.

Concrete	**Special Provision 90M-7181**
Concrete Curing Materials	**SECTION 1400**

3.0 CONSTRUCTION REQUIREMENTS.

Subsection 701.03(e). Delete the second paragraph of this subsection and replace with the following:

For placement limitations refer to **Special Provision 90M-7181**.

Fog all bridge deck placements. Begin the fogging immediately behind the finishing operations. Maintain the fogging to produce a “gloss to semi-gloss water sheen” on the surface until the curing is applied. Apply the fog over the entire placement width. Reduce fogging only if excess water accumulates on the surface and begins to run off.

Produce a fog spray from nozzles that atomize the droplets capable of keeping a large surface area damp without depositing excess water. Use high pressure equipment that generates at least 1200 psi at 2.2 gpm (8.3 MPa at 8.3 L/minute), or low pressure equipment having nozzles capable of supplying a maximum flow rate of 1.6 gpm (6.1 L/minute). Mount the fogging equipment on finishing equipment or other equipment that may immediately follow the finishing equipment. Use hand-held fogging apparatus only for the concrete under the finishing equipment that is not reachable by mounted fogging equipment, for corners not covered by machine fogging, and in the event that advancement of the finishing equipment is delayed.

Maintain environmental conditions and concrete temperature such that the evaporation rate is less than 0.2 lb/sq ft/hr (1.0 kg/sq m/hr). The effects of the required continuous fogging will not be considered in the estimation of the evaporation rate. This may require placing the deck at night, in the early morning or on another day. The evaporation rate (as determined in the American Concrete Institute Manual of Concrete Practice 305R, Chapter 2) is a function of air temperature, concrete temperature, wind speed, and humidity.

Just prior to and at least once per hour during placement of the concrete, measure and record the air temperature, concrete temperature, wind speed, and humidity. Take the air temperature, wind and humidity measurements approximately 12 inches (300 mm) above the surface of the deck. With this information, determine the evaporation rate by using the KDOT supplied software or by using Figure 2.1.5 from the above reference (copy attached). When the evaporation rate is equal to or above 0.2 lb/sq ft/hr (1.0 kg/sq m/hr), take measures (such as installing wind breaks, cooling the concrete, sun screens etc.) to create and maintain an evaporation rate less than 0.2 lb/sq ft/hr (1.0 kg/sq m/hr) on the entire bridge deck.

During the preconstruction conference, submit an acceptable Quality Control Plan detailing the equipment (for both determining and controlling the evaporation rate) and procedures used to minimize the evaporation rate. Follow the same Contractor's Concrete Structures Quality Control Plan as outlined in KDOT's Construction Manual, Part V.

S**ubsection 701.03(e). Delete the ninth paragraph of this subsection and replace with the following:**

Place concrete by conveyor belt or concrete bucket. The placement by pumping will only be allowed in limited circumstances and with prior approval from the KDOT Bureau of Materials and Research.

Subsection 701.03(g). Delete this subsection and add the following:

Strike the bridge deck off with a vibrating screed or single-drum roller screed. Finish the surface by a burlap drag or metal pan mounted to the finishing equipment. Use a float, roller or other approved device behind the burlap drag or metal plan to remove any local irregularities. The finisher may be self-propelled or it may be propelled by manually operated winches. The screed must be self-oscillating and it may operate or finish from a position transverse or longitudinal to the bridge roadway centerline. Prior to commencing concreting operations, position the finisher throughout the proposed placement area, as directed by the Engineer, to permit verification of the reinforcing steel positioning. Irregular sections may be finished by other methods approved by the Engineer.

The addition of water or precure/finishing aid to the surface of concrete to assist in finishing operations is prohibited.

Tining of plastic concrete is prohibited on (LC-HPC) concrete. All concrete surfaces must be reasonably true and even, free from stone pockets, excessive depressions or projections beyond the surface.

Subsection 701.03(h). Delete this subsection and replace with the following:

Cure all newly placed concrete beginning immediately after finishing, and continue uninterrupted for at least 14 days. Cure by the Water Method With Waterproof Cover as described below. Cure all pedestrian walkway surfaces in the same manner as the bridge deck. Curing compounds are prohibited during the 14 day curing period.

<u>Water With Waterproof Cover</u>

Apply fog continuously from the time of concrete strike-off until the concrete is covered with wet burlap. Mount fogging equipment on the finishing equipment that complies with subsection 701.03(e) of this special provision. Do not allow water to drip, flow or puddle on the concrete surface during fogging, placement of absorptive material, or at any time before the concrete has achieved final set.

Apply 1 layer of wet burlap within 10 minutes of concrete strike-off followed by a second layer of wet burlap within 5 minutes. Do not allow the surface to dry after the strike-off, or at any time during the cure period.

Maintain the wet burlap in a fully wet condition using a misting hose until the concrete has set sufficiently to allow foot traffic. At that time, place soaker hoses on the burlap, and supply running water continuously to maintain continuous saturation of all burlap material to the entire concrete surface.

Place white polyethylene film on top of the soaker hoses covering the entire concrete surface on the evening after the day of placement of the (LC HPC) Concrete. Use sheets of the widest practical width and overlap adjacent sheets a minimum of 6 inches (150 mm) and tightly sealed with pressure sensitive tape, mastic, glue, or other approved methods to form a complete waterproof cover of the entire concrete surface. Secure the polyethylene film so that wind will not displace it. Should any portion of the sheets be broken or damaged before expiration of the curing period, immediately repair the broken or damaged portions. Replace sections that have lost their waterproof qualities.

Inspect the concrete surface once every 6 hours for the entirety of the 14 day curing period, so that all areas remain wet for the entire curing period and all curing requirements are satisfied.

Documentation. Provide the Engineer with a daily inspection set that includes:

- documentation that identifies any deficiencies found (including location of deficiency);
- documentation of corrective measures taken;
- a statement of certification that all areas are wet and all curing material is in place on the entire bridge deck;

- documentation showing the time and date of the inspection and the inspector's signature.

Cold Weather Curing. When concrete is being placed in cold weather, do so in accordance with the requirements provided in Division 400.

When concrete is being placed and the ambient air temperature may be expected to drop below 40ºF(5ºC) during the curing period or when the ambient air temperature is expected to drop more than 25°F(14°C) below the temperature of the concrete during the first 24 hours after placement, provide suitable measures such as straw, additional burlap, or other suitable blanketing materials, and/or housing and artificial heat to maintain the concrete and girder temperatures between 55ºF (13ºC) and 75ºF (24ºC) as measured on the upper and lower surfaces of the concrete. Enclose the area underneath the deck and heat so that the temperature of the surrounding air is as close as possible to the temperature of concrete and between 55ºF (13ºC) and 75ºF (24ºC). Maintain wet burlap and polyethylene cover during the entire 14 day curing period. After the completion of the required curing period, remove the curing and protection so that the temperature of the concrete during the first 24 hours does not fall more than 25°F (14°C).

Curing Membrane. At the end of the 14-day curing period remove the wet burlap and polyethylene and within 30 minutes, apply two coats of curing membrane to the concrete. Apply the curing membrane when no free water remains on the surface but while the surface is still wet. The application rate of each coat of curing membrane is as prescribed by the manufacturer with a minimum spreading rate per coat of one liter per six square meters of concrete surface. If the concrete is dry or becomes dry, thoroughly wet it with water applied as a fog spray by means of approved equipment. Spray the second coat immediately after and at right angles to the first application.

Protect the curing membrane against marring for a period of at least 7 days. Give any marred or otherwise disturbed membrane an additional coating. Should the curing membrane be subjected to continuous injury, the Engineer may require wet burlap, polyethylene sheeting or other approved impermeable material to be applied at once.

Construction loads on the new one-course deck are subject to these limitations:

- Only foot traffic is allowed on the one-course deck during the 14-day curing period. Work to place reinforcing steel or forms for the bridge rail or barrier on the bridge deck is allowed 3 days after the concrete is placed, provided the curing is maintained on any exposed deck by keeping it wet during the 14-day curing period.
- Light truck traffic (gross vehicle weight less than 5 tons (5 Mg)) is allowed on the one-course deck 14 days after the concrete is placed.

- Legal loads are allowed on the one-course deck 14 days after the concrete is placed.
- If the Engineer approves, heavy stationary loads (such as material stockpiles) may be allowed on the one-course deck 14 days after the concrete is placed. The Contractor must submit, to the Engineer for consideration, the weight of the material and the footprint pressure of the load.
- If the Engineer approves, vehicle loads greater than legal loads may be allowed on the bridge deck 28 days after the deck pour is completed. The Contractor must submit, to the Engineer for consideration, the axle (or track) spacing and width, the size of each tire (or track length and width) and their weight.
- The use of equipment which causes vibration will only be allowed to be used under the supervision of the Engineer.

Subsection 701.03, Add this subsection:

Trial Slab

For each (LC-HPC) concrete bridge deck, construct a trial slab of the dimensions shown in the Contract Documents to demonstrate the ability to handle, place, finish and cure the (LC-HPC) concrete bridge deck.

After the trail trial batch complies with the requirements of **Special Provision 90M-7181,** construct a trial slab not later than 30 days prior to placing concrete in the bridge deck. Construct the trial slab that complies with the details of the Contract Documents and the same concrete that is to be placed in the deck and was approved in the trial batch. Submit the location of the trial slab for approval by the Engineer. Place, finish, and cure as required by the contract documents using the same personnel, methods and equipment that the Contractor intends to use on the bridge deck. The Engineer will determine the air void characteristics using the Air Void Analyzer (AVA) in accordance with Special Provision 90M-156 (latest revision). Acceptance of the trial slab is contingent upon demonstrating that the requirements of this specification are satisfied for placement, consolidation, finishing, curing, grinding and grooving.

Not less than one day after construction of the trial slab, core 4 full-depth 4 inch (100 mm) diameter cores, one from each quadrant of the trial slab, and forward them to the Engineer for visual inspection of degree of consolidation.

Do not commence placement of (LC-HPC) concrete in the deck until permission is given by the KDOT Bureau of Materials and Research. Permission to place will be based on the Contractor’s ability to adequately place, finish, cure, grind and groove the concrete and on verification by the Engineer that adequate consolidation was achieved. Granting of permission to place concrete will be given or denied within 24 hours of receiving the cores from the Contractor, and is not contingent on the results of the air parameter test. If an additional trial slab is deemed necessary by the Engineer, it will be paid for at the contract unit price for Trial Slab.

Grinding and Grooving

For (LC-HPC) concrete, perform grinding on hardened concrete after the curing period to achieve a plane surface and grooving of the final wearing surface as shown in the Contract Documents.

Correct surface variations exceeding 1/8 inch (3 mm) in 10 feet (3 m) by use of an approved profiling device, or other methods approved by the Engineer after the curing period.

Use a self-propelled grinding machine with diamond blades mounted on a multi-blade arbor. Avoid using equipment that causes excessive ravels, aggregate fractures, or spalls. Use vacuum equipment or other continuous methods to remove grinding slurry and residue.

Once the grinding has been achieved, give the surface a suitable texture by transverse grooving. Use diamond blades mounted on a self-propelled machine that is designed for texturing pavement. Use equipment that does not cause strain, excessive raveling, aggregate fracture, spalls, disturbance of the transverse or longitudinal joint, or damage to the existing concrete surface. Make the grooving approximately 3/16 inch (5 mm) in width at 3/4 inch (20 mm) centers and the groove depth approximately 1/8 inch (3 mm). For bridges with drains, the transverse grooving should terminate approximately 2 feet (0.6 m) in from the gutter line at the base of the curb. Continuously remove all slurry residue resulting from the texturing operation.

Post-Construction Conference.

At the completion of the deck placement, curing, grinding and grooving for a bridge using (LC-HPC) concrete, a post-construction conference will be held with all parties that participated in the planning and construction present. All problems and successes for the project shall be discussed and recorded by the Engineer at this meeting.

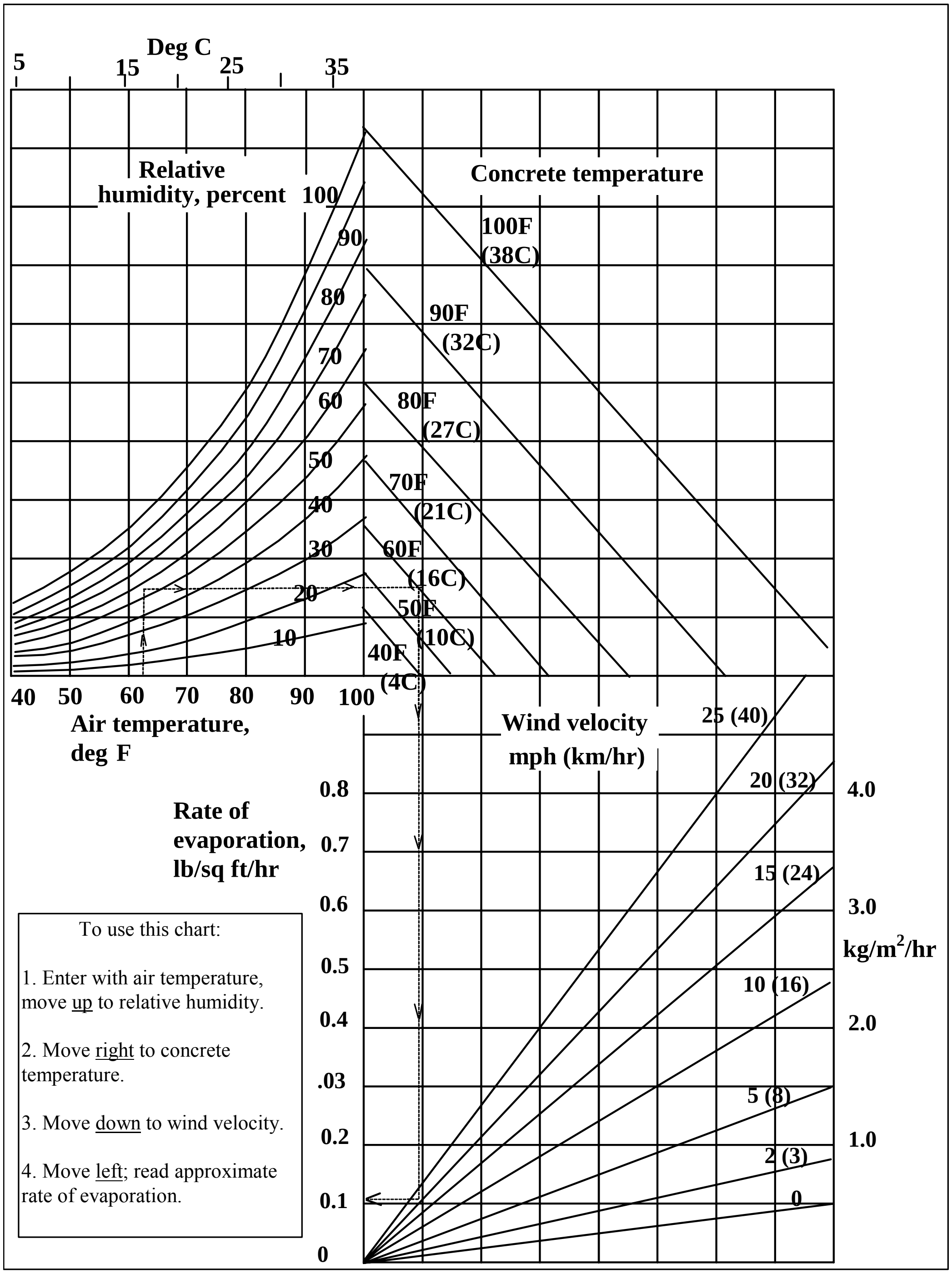
4.0 MEASUREMENT AND PAYMENT.

Grade * (AE)(LC-HPC) Concrete will measure the by the cubic yard (cu m), Trial Slab by the cubic yard (cu m). Measurement will be on the neat lines of the structure as shown on the Plans. No deductions are made for reinforcing steel and pile heads extending into the concrete.

Payment for "Grade * (AE)(LC-HPC)" and “Trial Slab” at the Contract unit price is full compensation for the specified work.

09-02-04 BD (BS)(RE)
7190

STANDARD PRACTICE FOR CURING CONCRETE



Effect of concrete and air temperatures, relative humidity, and wind velocity on the rate of evaporation of surface moisture from concrete. This chart provides a graphic method of estimating the loss of surface moisture for various weather conditions. To use the chart, follow the four steps outlined above. When the evaporation rate exceeds 0.2 lb/ft^2/hr (1.0 kg/ m^2/hr), measures shall be taken to prevent excessive moisture loss from the surface of unhardened concrete; when the rate is less than 0.2 lb/ft^2/hr (1.0 kg/ m^2/hr) such measures may be needed. When excessive moisture loss is not prevented, plastic cracking is likely to occur.

KANSAS DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION TO THE
STANDARD SPECIFICATIONS, 1990 EDITION

NOTE: This special provision is generally written in the imperative mood. The subject, "the *Contractor*" is implied. Also implied in this language are "*shall*", "*shall be*", or similar words and phrases. The word "*will*" generally pertains to decisions or actions of the Kansas Department of Transportation.

LOW CRACKING – HIGH PERFORMANCE CONCRETE (LC-HPC) CONSTRUCTION

1.0 DESCRIPTION.

Construct the concrete bridge deck designated in the Contract Documents that complies with Section 701 and this Special Provision.

BID ITEMS	**UNIT**
Concrete Grade * (AE)(LC-HPC) * Grade of Concrete	Cubic yard (cu m)
Trial Slab	Cubic yard (cu m)

2.0 MATERIALS.

Concrete	**Special Provision 90M-7181**
Concrete Curing Materials	**SECTION 1400**

3.0 CONSTRUCTION REQUIREMENTS.

Subsection 701.03(e). Delete the second paragraph of this subsection and replace with the following:

For placement limitations refer to **Special Provision 90M-7181**.

Fog all bridge deck placements. Begin the fogging immediately behind the finishing operations. Maintain the fogging to produce a “gloss to semi-gloss water sheen” on the surface until the curing is applied. Apply the fog over the entire placement width. Reduce fogging only if excess water accumulates on the surface and begins to run off.

Produce a fog spray from nozzles that atomize the droplets capable of keeping a large surface area damp without depositing excess water. Use high pressure equipment that generates at least 1200 psi at 2.2 gpm (8.3 MPa at 8.3 L/minute), or low pressure equipment having nozzles capable of supplying a maximum flow rate of 1.6 gpm (6.1 L/minute). Mount the fogging equipment on finishing equipment or other equipment that may immediately follow the finishing equipment. Use hand-held fogging apparatus only for the concrete under the finishing equipment that is not reachable by mounted fogging equipment, for corners not covered by machine fogging, and in the event that advancement of the finishing equipment is delayed.

Maintain environmental conditions and concrete temperature such that the evaporation rate is less than 0.2 lb/sq ft/hr (1.0 kg/sq m/hr). The effects of the required continuous fogging will not be considered in the estimation of the evaporation rate. This may require placing the deck at night, in the early morning or on another day. The evaporation rate (as determined in the American Concrete Institute Manual of Concrete Practice 305R, Chapter 2) is a function of air temperature, concrete temperature, wind speed, and humidity.

Just prior to and at least once per hour during placement of the concrete, measure and record the air temperature, concrete temperature, wind speed, and humidity. Take the air temperature, wind and humidity measurements approximately 12 inches (300 mm) above the surface of the deck. With this information, determine the evaporation rate by using the KDOT supplied software or by using Figure 2.1.5 from the above reference (copy attached). When the evaporation rate is equal to or above 0.2 lb/sq ft/hr (1.0 kg/sq m/hr), take measures (such as installing wind breaks, cooling the concrete, sun screens etc.) to create and maintain an evaporation rate less than 0.2 lb/sq ft/hr (1.0 kg/sq m/hr) on the entire bridge deck.

During the preconstruction conference, submit an acceptable Quality Control Plan detailing the equipment (for both determining and controlling the evaporation rate) and procedures used to minimize the evaporation rate. Follow the same Contractor's Concrete Structures Quality Control Plan as outlined in KDOT's Construction Manual, Part V.

Subsection 701.03(e). Delete the ninth paragraph of this subsection and replace with the following:

Place concrete by conveyor belt or concrete bucket. The placement by pumping will only be allowed in limited circumstances and with prior approval from the KDOT Bureau of Materials and Research.

Subsection 701.03(g). Delete this subsection and add the following:

Strike the bridge deck off with a vibrating screed or single-drum roller screed. Finish the surface by a burlap drag or metal pan mounted to the finishing equipment. Use a float, roller or other approved device behind the burlap drag or metal plan to remove any local irregularities. The finisher may be self-propelled or it may be propelled by manually operated winches. The screed must be self-oscillating and it may operate or finish from a position transverse or longitudinal to the bridge roadway centerline. Prior to commencing concreting operations, position the finisher throughout the proposed placement area, as directed by the Engineer, to permit verification of the reinforcing steel positioning. Irregular sections may be finished by other methods approved by the Engineer.

The addition of water or precure/finishing aid to the surface of concrete to assist in finishing operations is prohibited.

Tining of plastic concrete is prohibited on (LC-HPC) concrete. All concrete surfaces must be reasonably true and even, free from stone pockets, excessive depressions or projections beyond the surface.

Subsection 701.03(h). Delete this subsection and replace with the following:

Cure all newly placed concrete beginning immediately after finishing, and continue uninterrupted for at least 14 days. Cure by the Water Method With Waterproof Cover as described below. Cure all pedestrian walkway surfaces in the same manner as the bridge deck. Curing compounds are prohibited during the 14 day curing period.

Water With Waterproof Cover

Apply fog continuously from the time of concrete strike-off until the concrete is covered with wet burlap. Mount fogging equipment on the finishing equipment that complies with subsection 701.03(e) of this special provision. Do not allow water to drip, flow or puddle on the concrete surface during fogging, placement of absorptive material, or at any time before the concrete has achieved final set.

Apply 1 layer of wet burlap within 10 minutes of concrete strike-off followed by a second layer of wet burlap within 5 minutes. Do not allow the surface to dry after the strike-off, or at any time during the cure period.

Maintain the wet burlap in a fully wet condition using a misting hose until the concrete has set sufficiently to allow foot traffic. At that time, place soaker hoses on the burlap, and supply running water continuously to maintain continuous saturation of all burlap material to the entire concrete surface.

Place white polyethylene film on top of the soaker hoses covering the entire concrete surface on the evening after the day of placement of the (LC HPC) Concrete. Use sheets of the widest practical width and overlap adjacent sheets a minimum of 6 inches (150 mm) and tightly sealed with pressure sensitive tape, mastic, glue, or other approved methods to form a complete waterproof cover of the entire concrete surface. Secure the polyethylene film so that wind will not displace it. Should any portion of the sheets be broken or damaged before expiration of the curing period, immediately repair the broken or damaged portions. Replace sections that have lost their waterproof qualities.

Inspect the concrete surface once every 6 hours for the entirety of the 14 day curing period, so that all areas remain wet for the entire curing period and all curing requirements are satisfied.

Documentation. Provide the Engineer with a daily inspection set that includes:

- documentation that identifies any deficiencies found (including location of deficiency);
- documentation of corrective measures taken;
- a statement of certification that all areas are wet and all curing material is in place on the entire bridge deck;

- documentation showing the time and date of the inspection and the inspector's signature.

Cold Weather Curing. When concrete is being placed in cold weather, do so in accordance with the requirements provided in Division 400.

When concrete is being placed and the ambient air temperature may be expected to drop below 40ºF (5ºC) during the curing period or when the ambient air temperature is expected to drop more than 25°F (14°C) below the temperature of the concrete during the first 24 hours after placement, provide suitable measures such as straw, additional burlap, or other suitable blanketing materials, and/or housing and artificial heat to maintain the concrete and girder temperatures between 55ºF (13ºC) and 75ºF (24ºC) as measured on the upper and lower surfaces of the concrete. Enclose the area underneath the deck and heat so that the temperature of the surrounding air is as close as possible to the temperature of concrete and between 55ºF (13ºC) and 75ºF (24ºC). Maintain wet burlap and polyethylene cover during the entire 14 day curing period. After the completion of the required curing period, remove the curing and protection so that the temperature of the concrete during the first 24 hours does not fall more than 25°F (14°C).

Curing Membrane. At the end of the 14-day curing period remove the wet burlap and polyethylene and within 30 minutes, apply two coats of curing membrane to the concrete. Apply the curing membrane when no free water remains on the surface but while the surface is still wet. The application rate of each coat of curing membrane is as prescribed by the manufacturer with a minimum spreading rate per coat of one liter per six square meters of concrete surface. If the concrete is dry or becomes dry, thoroughly wet it with water applied as a fog spray by means of approved equipment. Spray the second coat immediately after and at right angles to the first application.

Protect the curing membrane against marring for a period of at least 7 days. Give any marred or otherwise disturbed membrane an additional coating. Should the curing membrane be subjected to continuous injury, the Engineer may require wet burlap, polyethylene sheeting or other approved impermeable material to be applied at once.

Construction loads on the new one-course deck are subject to these limitations:

- Only foot traffic is allowed on the one-course deck during the 14-day curing period. Work to place reinforcing steel or forms for the bridge rail or barrier on the bridge deck is allowed 3 days after the concrete is placed, provided the curing is maintained on any exposed deck by keeping it wet during the 14-day curing period.
- Light truck traffic (gross vehicle weight less than 5 tons (5 Mg)) is allowed on the one-course deck 14 days after the concrete is placed.

- Legal loads are allowed on the one-course deck 14 days after the concrete is placed.
- If the Engineer approves, heavy stationary loads (such as material stockpiles) may be allowed on the one-course deck 14 days after the concrete is placed. The Contractor must submit, to the Engineer for consideration, the weight of the material and the footprint pressure of the load.
- If the Engineer approves, vehicle loads greater than legal loads may be allowed on the bridge deck 28 days after the deck pour is completed. The Contractor must submit, to the Engineer for consideration, the axle (or track) spacing and width, the size of each tire (or track length and width) and their weight.
- The use of equipment which causes vibration will only be allowed to be used under the supervision of the Engineer.

Subsection 701.03, Add this subsection:

Trial Slab

For each (LC-HPC) concrete bridge deck, construct a trial slab of the dimensions shown in the Contract Documents to demonstrate the ability to handle, place, finish and cure the (LC-HPC) concrete bridge deck.

After the trail batch complies with the requirements of **Special Provision 90M-7181,** construct a trial slab not later than 30 days prior to placing concrete in the bridge deck. Construct the trial slab that complies with the details of the Contract Documents and the same concrete that is to be placed in the deck and was approved in the trial batch. Submit the location of the trial slab for approval by the Engineer. Place, finish, and cure as required by the contract documents using the same personnel, methods and equipment that the Contractor intends to use on the bridge deck. The Engineer will determine the air void characteristics using the Air Void Analyzer (AVA) in accordance with Special Provision 90M-156 (latest revision). Acceptance of the trial slab is contingent upon demonstrating that the requirements of this specification are satisfied for placement, consolidation, finishing, curing, grinding and grooving.

Not less than one day after construction of the trial slab, core 4 full-depth 4 inch (100 mm) diameter cores, one from each quadrant of the trial slab, and forward them to the Engineer for visual inspection of degree of consolidation.

Do not commence placement of (LC-HPC) concrete in the deck until permission is given by the KDOT Bureau of Materials and Research. Permission to place will be based on the Contractor’s ability to adequately place, finish, and cure the concrete and on verification by the Engineer that adequate consolidation was achieved. Granting of permission to place concrete will be given or denied within 24 hours of receiving the cores from the Contractor, and is not contingent on the results of the air parameter test. If an additional trial slab is deemed necessary by the Engineer, it will be paid for at the contract unit price for Trial Slab.

Grinding and Grooving

For (LC-HPC) concrete, perform grinding on hardened concrete after the curing period to achieve a plane surface and grooving of the final wearing surface as shown in the Contract Documents.

Correct surface variations exceeding 1/8 inch (3 mm) in 10 feet (3 m) by use of an approved profiling device, or other methods approved by the Engineer after the curing period.

Use a self-propelled grinding machine with diamond blades mounted on a multi-blade arbor. Avoid using equipment that causes excessive ravels, aggregate fractures, or spalls. Use vacuum equipment or other continuous methods to remove grinding slurry and residue.

Once the grinding has been achieved, give the surface a suitable texture by transverse grooving. Use diamond blades mounted on a self-propelled machine that is designed for texturing pavement. Use equipment that does not cause strain, excessive raveling, aggregate fracture, spalls, disturbance of the transverse or longitudinal joint, or damage to the existing concrete surface. Make the grooving approximately 3/16 inch (5 mm) in width at 3/4 inch (20 mm) centers and the groove depth approximately 1/8 inch (3 mm). For bridges with drains, the transverse grooving should terminate approximately 2 feet (0.6 m) in from the gutter line at the base of the curb. Continuously remove all slurry residue resulting from the texturing operation.

Post-Construction Conference.

At the completion of the deck placement, curing, grinding and grooving for a bridge using (LC-HPC) concrete, a post-construction conference will be held with all parties that participated in the planning and construction present. All problems and successes for the project shall be discussed and recorded by the Engineer at this meeting.

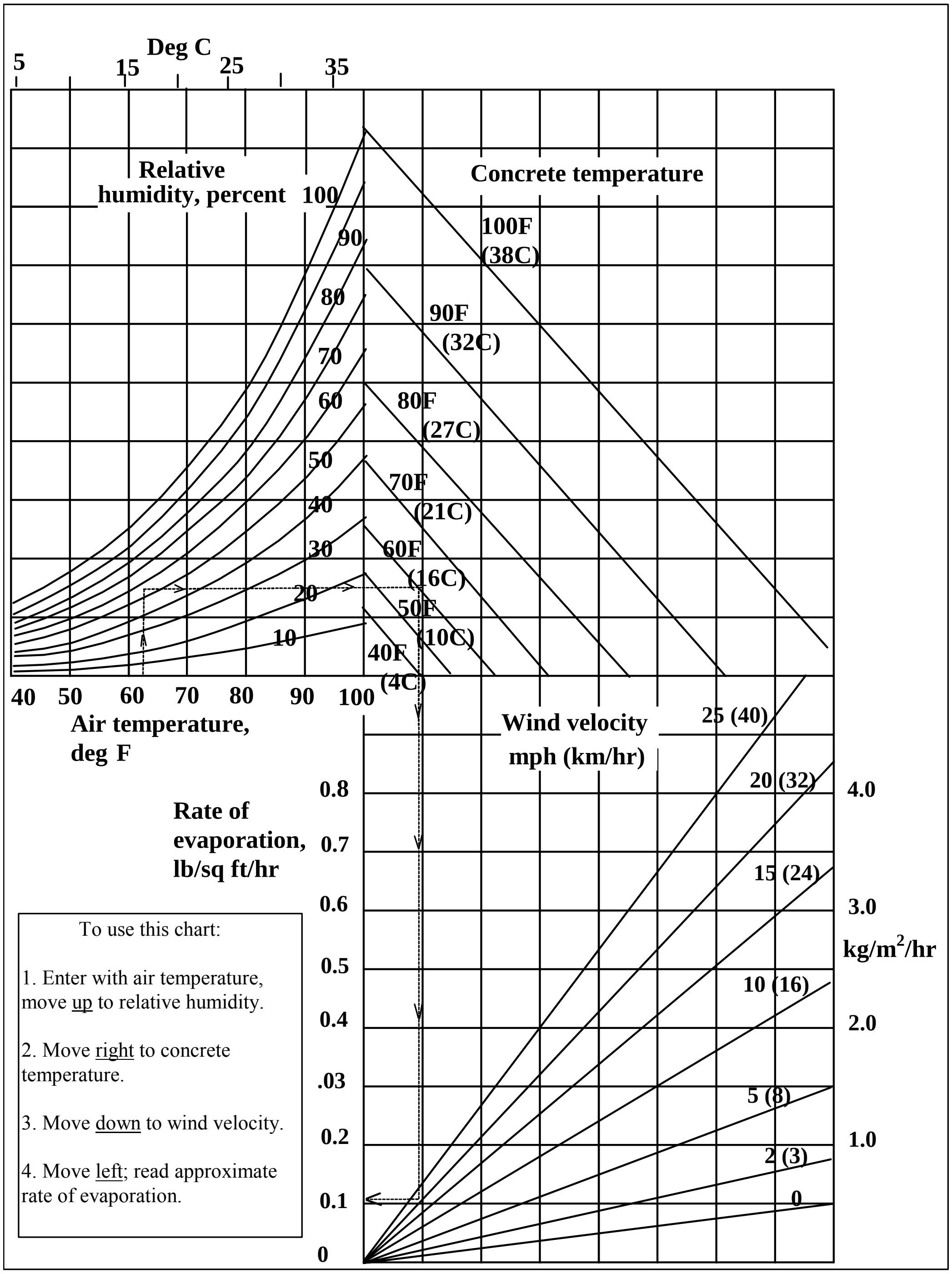
4.0 MEASUREMENT AND PAYMENT.

Grade * (AE)(LC-HPC) Concrete will measure the by the cubic yard (cu m), Trial Slab by the cubic yard (cu m). Measurement will be on the neat lines of the structure as shown on the Plans. No deductions are made for reinforcing steel and pile heads extending into the concrete.

Payment for "Grade * (AE)(LC-HPC)" and “Trial Slab” at the Contract unit price is full compensation for the specified work.

08-04-05 BD (BS)(RE)
7276

STANDARD PRACTICE FOR CURING CONCRETE



Effect of concrete and air temperatures, relative humidity, and wind velocity on the rate of evaporation of surface moisture from concrete. This chart provides a graphic method of estimating the loss of surface moisture for various weather conditions. To use the chart, follow the four steps outlined above. When the evaporation rate exceeds 0.2 lb/ft^2/hr (1.0 kg/ m^2/hr), measures shall be taken to prevent excessive moisture loss from the surface of unhardened concrete; when the rate is less than 0.2 lb/ft^2/hr (1.0 kg/ m^2/hr) such measures may be needed. When excessive moisture loss is not prevented, plastic cracking is likely to occur.

90M-7332
Sheet 1 of 7

KANSAS DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION TO THE
STANDARD SPECIFICATIONS, 1990 EDITION

NOTE: This special provision is generally written in the imperative mood. The subject, "the *Contractor*" is implied. Also implied in this language are "*shall*", "*shall be*", or similar words and phrases. The word "*will*" generally pertains to decisions or actions of the Kansas Department of Transportation.

LOW CRACKING – HIGH PERFORMANCE CONCRETE (LC-HPC) CONSTRUCTION

1.0 DESCRIPTION.

Construct the concrete bridge deck designated in the Contract Documents that complies with Section 701 and this Special Provision.

BID ITEMS	UNIT
Concrete Grade * (AE)(LC-HPC) * Grade of Concrete	Cubic yard (cu m)
Qualification Slab	Cubic yard (cu m)

2.0 MATERIALS.

Concrete ....**Special Provision 90M-7295**
Concrete Curing Materials ....**SECTION 1400**

3.0 CONSTRUCTION REQUIREMENTS.

Subsection 701.03(e). Delete the second paragraph of this subsection and replace with the following:

For placement limitations refer to **Special Provision 90M-7295**.

Fog all bridge deck placements. Begin the fogging immediately behind the finishing operations. Maintain the fogging to produce a "gloss to semi-gloss water sheen" on the surface until the curing is applied. Apply the fog over the entire placement width. Reduce fogging only if excess water accumulates on the surface and begins to run off. Do not use accumulated water from fogging as a finishing aid. Do not allow water to drip, flow or puddle on the concrete surface during fogging, placement of absorptive material, or at any time before the concrete has achieved final set.

Produce a fog spray from nozzles that atomize the droplets capable of keeping a large surface area damp without depositing excess water. Use high pressure equipment that generates at least 1200 psi at 2.2 gpm (8.3 MPa at 8.3 L/minute), or low pressure equipment having nozzles capable of supplying a maximum flow rate of 1.6 gpm (6.1 L/minute). Mount the fogging equipment on finishing equipment or other equipment that may immediately follow the finishing equipment. Use hand-held fogging apparatus for the concrete under the finishing equipment that is not reachable by mounted fogging equipment, for corners not covered by machine fogging, and for all exposed concrete in the event that advancement of the finishing equipment is delayed.

Maintain environmental conditions and concrete temperature such that the evaporation rate is less than 0.2 lb/sq ft/hr (1.0 kg/sq m/hr). The effects of the required continuous fogging will not be considered in the estimation of the evaporation rate. This may require placing the deck at night, in the early morning or on another day. The evaporation rate (as determined in the American Concrete Institute Manual of Concrete Practice 305R, Chapter 2) is a function of air temperature, concrete temperature, wind speed, and humidity.

Just prior to and at least once per hour during placement of the concrete, measure and record the air temperature, concrete temperature, wind speed, and humidity. Take the air temperature, wind and humidity measurements approximately 12 inches (300 mm) above the surface of the deck. With this information, determine the evaporation rate by using the KDOT supplied software or by using Figure 2.1.5 from the above reference (copy attached). When the evaporation rate is equal to or above 0.2 lb/sq ft/hr (1.0 kg/sq m/hr), take measures (such as installing wind breaks, cooling the concrete, sun screens etc.) to create and maintain an evaporation rate less than 0.2 lb/sq ft/hr (1.0 kg/sq m/hr) on the entire bridge deck.

During the preconstruction conference, submit an acceptable Quality Control Plan detailing the equipment (for both determining and controlling the evaporation rate) and procedures used to minimize the evaporation rate. Follow the same Contractor's Concrete Structures Quality Control Plan as outlined in KDOT's Construction Manual, Part V.

Subsection 701.03(e). Delete the ninth paragraph of this subsection and replace with the following:
Place concrete by conveyor belt or concrete bucket. Pumping of LC-HPC will be allowed if the contractor can show proficiency when placing the approved mix during construction of the qualification slab. Placement by pump will also be allowed with prior approval of the Engineer contingent upon successful placement by pump of the approved mix at least 15 days prior to placing concrete in the bridge deck.

Subsection 701.03(g). Delete this subsection and add the following:

Strike the bridge deck off with a vibrating screed or single-drum roller screed. Finish the surface by a burlap drag or metal pan mounted to the finishing equipment. Use a float or other approved device behind the burlap drag or metal plan to remove any local irregularities. The finisher may be self-propelled or it may be propelled by manually operated winches. The screed must be self-oscillating and it may operate or finish from a position transverse or longitudinal to the bridge roadway centerline. Prior to commencing concreting operations, position the finisher throughout the proposed placement area, as directed by the Engineer, to permit verification of the reinforcing steel positioning. Irregular sections may be finished by other methods approved by the Engineer.

The addition of water or precure/finishing aid to the surface of concrete to assist in finishing operations is prohibited.

Tining of plastic concrete is prohibited on (LC-HPC) concrete. All concrete surfaces must be reasonably true and even, free from stone pockets, excessive depressions or projections beyond the surface.

Subsection 701.03(h). Delete this subsection and replace with the following:

Cure all newly placed concrete immediately after finishing, and continue uninterrupted for at least 14 days. Cure by the Water Method With Waterproof Cover as described below. Cure all pedestrian walkway surfaces in the same manner as the bridge deck. Cure barriers in the same manner as the bridge deck, except fogging is not required for the barriers. Curing compounds are prohibited during the 14 day curing period.

Water With Waterproof Cover

Apply 1 layer of wet burlap within 10 minutes of concrete strike-off followed by a second layer of wet burlap within 5 minutes. Do not allow the surface to dry after the strike-off, or at any time during the cure period.

Maintain the wet burlap in a fully wet condition using misting hoses, self-propelled, machine-mounted fogging equipment with effective fogging area spanning the deck width moving continuously across the entire burlap-covered surface, or other approved devices until the concrete has set sufficiently to allow foot traffic. At that time, place soaker hoses on the burlap, and supply running water continuously to maintain continuous saturation of all burlap material to the entire concrete surface.

Place white polyethylene film on top of the soaker hoses covering the entire concrete surface after soaker hoses have been placed, but not more than 12 hours after the placement of the (LC-HPC) Concrete. Use sheets of the widest practical width and overlap adjacent sheets a minimum of 6 inches (150 mm) and tightly sealed with pressure sensitive tape, mastic, glue, or other approved methods to form a complete waterproof cover of the entire concrete surface. Secure the polyethylene film so that wind will not displace it. Should any portion of the sheets be broken or damaged before expiration of the curing period, immediately repair the broken or damaged portions. Replace sections that have lost their waterproof qualities.

If burlap and/or polyethylene film is temporarily removed for any reason during the curing period, soaker hoses shall be used to ensure that the entire exposed area is kept continuously wet. Saturated burlap and polyethylene film shall be replaced, resuming the specified curing conditions, as soon as possible.

Inspect the concrete surface once every 6 hours for the entirety of the 14 day curing period, so that all areas remain wet for the entire curing period and all curing requirements are satisfied.

Documentation. Provide the Engineer with a daily inspection set that includes:

- documentation that identifies any deficiencies found (including location of deficiency);
- documentation of corrective measures taken;
- a statement of certification that all areas are wet and all curing material is in place on the entire bridge deck;
- documentation showing the time and date of all inspections and the inspector's signature.
- documentation of any temporary removal of curing materials including location, date and time, length of time curing was removed, and means taken to ensure exposed area was kept continuously wet.

Cold Weather Curing. When concrete is being placed in cold weather, do so in accordance with the requirements in **Special Provision 90M-7295**.

When concrete is being placed and the ambient air temperature may be expected to drop below 40ºF (5ºC) during the curing period or when the ambient air temperature is expected to drop more than 25°F (14°C) below the temperature of the concrete during the first 24 hours after placement, provide suitable measures such as straw, additional burlap, or other suitable blanketing materials, and/or housing and artificial heat to maintain the concrete and girder temperatures between 55ºF (13ºC) and 75ºF (24ºC) as measured on the upper and lower surfaces of the concrete. Enclose the area underneath the deck and heat so that the temperature of the surrounding air is as close as possible to the temperature of concrete and between 55ºF (13ºC) and 75ºF (24ºC). Maintain wet burlap and polyethylene cover during the entire 14 day curing period. After the completion of the required curing period, remove the curing and protection so that the temperature of the concrete during the first 24 hours does not fall more than 25°F (14°C).

Curing Membrane. At the end of the 14-day curing period remove the wet burlap and polyethylene and within 30 minutes, apply two coats of curing membrane to the concrete. Apply the curing membrane when no free water remains on the surface but while the surface is still wet. The application rate of each coat of curing membrane is as prescribed by the manufacturer with a minimum spreading rate per coat of one liter per six square meters of concrete surface. If the concrete is dry or becomes dry, thoroughly wet it with water applied as a fog spray by means of approved equipment. Spray the second coat immediately after and at right angles to the first application.

Protect the curing membrane against marring for a period of at least 7 days. Give any marred or otherwise disturbed membrane an additional coating. Should the curing membrane be subjected to continuous injury, the Engineer may require wet burlap, polyethylene sheeting or other approved impermeable material to be applied at once.

Construction loads on the new one-course deck are subject to these limitations:

- Only foot traffic is allowed on the one-course deck during the 14-day curing period. Work to place reinforcing steel or forms for the bridge rail or barrier on the bridge deck is allowed 3 days after the concrete is placed, provided the curing is maintained on any exposed deck by keeping it wet during the 14-day curing period.
- Legal loads are allowed on the one-course deck 14 days after the concrete is placed.
- If the Engineer approves, heavy stationary loads (such as material stockpiles) may be allowed on the one-course deck 14 days after the concrete is placed. The Contractor must submit, to the Engineer for consideration, the weight of the material and the footprint pressure of the load.
- If the Engineer approves, vehicle loads greater than legal loads may be allowed on the bridge deck 28 days after the deck pour is completed. The Contractor must submit, to the Engineer for consideration, the axle (or track) spacing and width, the size of each tire (or track length and width) and their weight.
- The use of equipment which causes vibration will only be allowed to be used under the supervision of the Engineer.

Subsection 701.03, Add this subsection:

Qualification Slab

For each (LC-HPC) concrete bridge deck, construct a qualification slab with the dimensions shown in the Contract Documents to demonstrate the ability to handle, place, finish and cure the (LC-HPC) concrete bridge deck.

After the qualification batch complies with the requirements of **Special Provision 90M-7295,** construct a qualification slab 15 to 45 days prior to placing concrete in the bridge deck. Construct the qualification slab so that it complies with the details of the Contract Documents using the same concrete that is to be placed in the deck and was approved in the qualification batch. Submit the location of the qualification slab for approval by the Engineer. Place, finish, and cure as required by the contract documents using the same personnel, methods and equipment that the Contractor intends to use on the bridge deck. The Engineer will determine the air void characteristics using the Air Void Analyzer (AVA) in accordance with Special Provision 90M-156 (latest revision). Acceptance of the qualification slab is contingent upon demonstrating that the requirements of this specification are satisfied for placement, consolidation, finishing, and curing.

Not less than one day after construction of the qualification slab, core 4 full-depth 4 inch (100 mm) diameter cores, one from each quadrant of the qualification slab, and forward them to the Engineer for visual inspection of degree of consolidation.

Do not commence placement of (LC-HPC) concrete in the deck until permission is given by the KDOT Bureau of Materials and Research. Permission to place will be based on the Contractor's ability to adequately place, finish, and cure the concrete and on verification by the Engineer that adequate consolidation was achieved. Granting of permission to place concrete will be given or denied within 24 hours of receiving the cores from the Contractor, and is not contingent on the results of the air parameter test. If an additional qualification slab is deemed necessary by the Engineer, it will be paid for at the contract unit price for Qualification Slab.

Grinding and Grooving

For (LC-HPC) concrete, perform grinding on hardened concrete for the entire deck surface after the curing period to achieve a plane surface and grooving of the final wearing surface as shown in the Contract Documents. Surface variations shall not exceed 1/8 inch (3 mm) in 10 feet (3 m) as measured using an approved profiling device, or other methods approved by the Engineer after the curing period.

Use a self-propelled grinding machine with diamond blades mounted on a multi-blade arbor. Avoid using equipment that causes excessive ravels, aggregate fractures, or spalls. Use vacuum equipment or other continuous methods to remove grinding slurry and residue.

Once the grinding has been achieved, give the surface a suitable texture by transverse grooving. Use diamond blades mounted on a self-propelled machine that is designed for texturing pavement. Grooving of the finished surface may be done with equipment that is not self-propelled providing that the contractor can show proficiency with the equipment. Use equipment that does not cause strain, excessive raveling, aggregate fracture, spalls, disturbance of the transverse or longitudinal joint, or damage to the existing concrete surface. Make the grooving approximately 3/16 inch (5 mm) in width at 3/4 inch (20 mm) centers and the groove depth approximately 1/8 inch (3 mm). For bridges with drains, the transverse grooving should terminate approximately 2 feet (0.6 m) in from the gutter line at the base of the curb. Continuously remove all slurry residue resulting from the texturing operation.

Post-Construction Conference.

At the completion of the deck placement, curing, grinding and grooving for a bridge using (LC-HPC) concrete, a post-construction conference will be held with all parties that participated in the planning and construction present. All problems and successes for the project shall be discussed and recorded by the Engineer at this meeting.

4.0 MEASUREMENT AND PAYMENT.

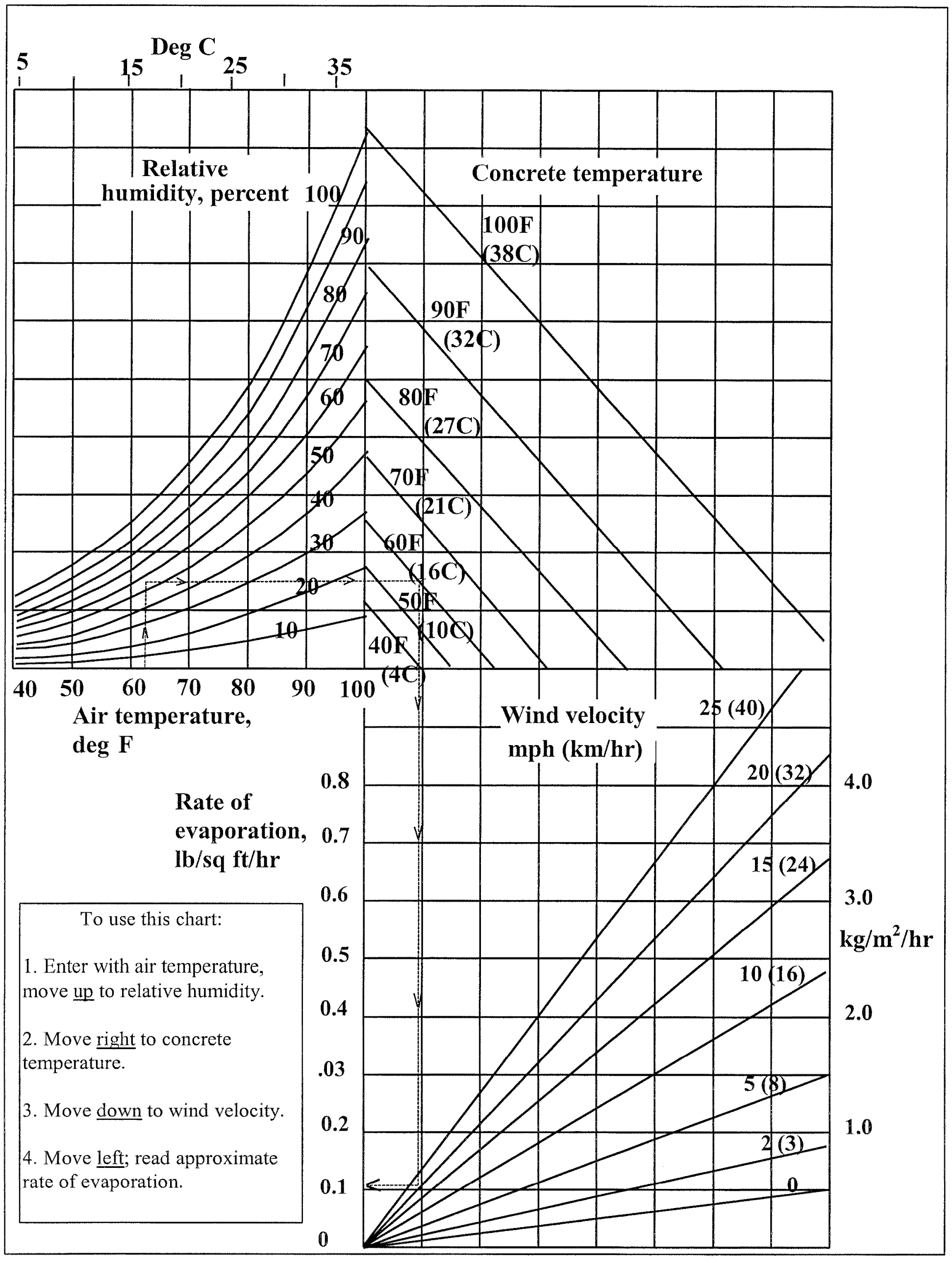
Grade * (AE)(LC-HPC) Concrete will measure the by the cubic yard (cu m), Qualification Slab by the cubic yard (cu m). Measurement will be on the neat lines of the structure as shown on the Plans. No deductions are made for reinforcing steel and pile heads extending into the concrete.

Payment for "Grade * (AE)(LC-HPC)" and "Qualification Slab" at the Contract unit price is full compensation for the specified work.

06-15-06 BD (BS)(RE)

90M-7332

STANDARD PRACTICE FOR CURING CONCRETE



Effect of concrete and air temperatures, relative humidity, and wind velocity on the rate of evaporation of surface moisture from concrete. This chart provides a graphic method of estimating the loss of surface moisture for various weather conditions. To use the chart, follow the four steps outlined above. When the evaporation rate exceeds 0.2 lb/ft^2/hr (1.0 kg/ m^2/hr), measures shall be taken to prevent excessive moisture loss from the surface of unhardened concrete; when the rate is less than 0.2 lb/ft^2/hr (1.0 kg/ m^2/hr) such measures may be needed. When excessive moisture loss is not prevented, plastic cracking is likely to occur.

KANSAS DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION TO THE
STANDARD SPECIFICATIONS, 1990 EDITION

NOTE: This special provision is generally written in the imperative mood. The subject, "the *Contractor*" is implied. Also implied in this language are "*shall*", "*shall be*", or similar words and phrases. The word "*will*" generally pertains to decisions or actions of the Kansas Department of Transportation.

LOW CRACKING – HIGH PERFORMANCE CONCRETE (LC-HPC) CONSTRUCTION

1.0 DESCRIPTION.

Construct the concrete bridge deck designated in the Contract Documents that complies with Section 701 and this Special Provision.

BID ITEMS	**UNIT**
Concrete Grade * (AE)(LC-HPC)	Cubic yard (cubic meter)
* Grade of Concrete	
Qualification Slab	Cubic yard (cubic meter)

2.0 MATERIALS.

Concrete ....**Special Provision 90P-5095**

Concrete Curing Materials ....**SECTION 1400**

3.0 CONSTRUCTION REQUIREMENTS.

S**ubsection 701.03(e). Delete the second paragraph of this subsection and replace with the following:**

For placement limitations refer to **Special Provision 90P-5095.**

Fog all bridge deck placements. Begin the fogging immediately behind the finishing operations. Maintain the fogging to produce a “gloss to semi-gloss water sheen” on the surface until the curing is applied. Apply the fog over the entire placement width. Reduce fogging only if excess water accumulates on the surface and begins to run off. Do not use accumulated water from fogging as a finishing aid. Do not allow water to drip, flow or puddle on the concrete surface during fogging, placement of absorptive material, or at any time before the concrete has achieved final set.

Produce a fog spray from nozzles that atomize the droplets capable of keeping a large surface area damp without depositing excess water. Use high pressure equipment that generates at least 1200 psi at 2.2 gpm (8.3 MPa at 8.3 L/minute), or low pressure equipment having nozzles capable of supplying a maximum flow rate of 1.6 gpm (6.1 L/minute). Mount the fogging equipment on finishing equipment or other equipment that may immediately follow the finishing equipment. Use hand-held fogging apparatus for the concrete under the finishing equipment that is not reachable by mounted fogging equipment, for corners not covered by machine fogging, and for all exposed concrete in the event that advancement of the finishing equipment is delayed.

Maintain environmental conditions and concrete temperature such that the evaporation rate is less than 0.2 lb/sq ft/hr (1.0 kg/sq m/hr). For LC-HPC concrete, the temperature of the mixed concrete immediately before placement must be at least 55°F (13ºC), but not more than 70°F (21ºC). With approval by the engineer, the temperature of the concrete may be adjusted 5°F (3ºC) above or below this range. The effects of the required continuous fogging will not be considered in the estimation of the evaporation rate. This may require placing the deck at night, in the early morning or on another day. The evaporation rate (as determined in the American Concrete Institute Manual of Concrete Practice 305R, Chapter 2) is a function of air temperature, concrete temperature, wind speed, and humidity.

Just prior to and at least once per hour during placement of the concrete, measure and record the air temperature, concrete temperature, wind speed, and humidity. Take the air temperature, wind and humidity measurements approximately 12 inches (300 mm) above the surface of the deck. With this information, determine the evaporation rate by using the KDOT supplied software or by using Figure 2.1.5 from the above reference (copy attached). When the evaporation rate is equal to or above 0.2 lb/sq ft/hr (1.0 kg/sq m/hr), take measures (such as installing wind breaks, cooling the concrete, sun screens etc.) to create and maintain an evaporation rate less than 0.2 lb/sq ft/hr (1.0 kg/sq m/hr) on the entire bridge deck.

During the preconstruction conference, submit an acceptable Quality Control Plan detailing the equipment (for both determining and controlling the evaporation rate and concrete temperature) and procedures used to minimize the evaporation rate. Follow the same Contractor's Concrete Structures Quality Control Plan as outlined in KDOT's Construction Manual, Part V.

Subsection 701.03(e). Delete the ninth paragraph of this subsection and replace with the following:

Place concrete by conveyor belt or concrete bucket. Pumping of LC-HPC will be allowed if the contractor can show proficiency when placing the approved mix during construction of the qualification slab. Placement by pump will also be allowed with prior approval of the Engineer contingent upon successful placement by pump of the approved mix at least 15 days prior to placing concrete in the bridge deck.

Subsection 701.03(g). Delete this subsection and add the following:

Strike the bridge deck off with a vibrating screed or single-drum roller screed. Finish the surface by a burlap drag or metal pan mounted to the finishing equipment. Use a float or other approved device behind the burlap drag or metal plan to remove any local irregularities. The finisher may be self-propelled or it may be propelled by manually operated winches. The screed must be self-oscillating and it may operate or finish from a position transverse or longitudinal to the bridge roadway centerline. Prior to commencing concreting operations, position the finisher throughout the proposed placement area, as directed by the Engineer, to permit verification of the reinforcing steel positioning. Irregular sections may be finished by other methods approved by the Engineer.

The addition of water or precure/finishing aid to the surface of concrete to assist in finishing operations is prohibited.

Tining of plastic concrete is prohibited on (LC-HPC) concrete. All concrete surfaces must be reasonably true and even, free from stone pockets, excessive depressions or projections beyond the surface.

Subsection 701.03(h). Delete this subsection and replace with the following:

Cure all newly placed concrete immediately after finishing, and continue uninterrupted for at least 14 days. Cure by the Water Method With Waterproof Cover as described below. Cure all pedestrian walkway surfaces in the same manner as the bridge deck. Cure barriers in the same manner as the bridge deck, except fogging is not required for the barriers. Curing compounds are prohibited during the 14 day curing period.

Water With Waterproof Cover

Apply 1 layer of wet burlap within 10 minutes of concrete strike-off followed by a second layer of wet burlap within 5 minutes. Do not allow the surface to dry after the strike-off, or at any time during the cure period.

Maintain the wet burlap in a fully wet condition using misting hoses, self-propelled, machine-mounted fogging equipment with effective fogging area spanning the deck width moving continuously across the entire burlap-covered surface, or other approved devices until the concrete has set sufficiently to allow foot traffic. At that time, place soaker hoses on the burlap, and supply running water continuously to maintain continuous saturation of all burlap material to the entire concrete surface.

Place white polyethylene film on top of the soaker hoses covering the entire concrete surface after soaker hoses have been placed, but not more than 12 hours after the placement of the (LC-HPC) Concrete. Use sheets of the widest practical width and overlap adjacent sheets a minimum of 6 inches (150 mm) and tightly sealed with pressure sensitive tape, mastic, glue, or other approved methods to form a complete waterproof cover of the entire concrete surface. Secure the polyethylene film so that wind will not displace it. Should any portion of the sheets be broken or damaged before expiration of the curing period, immediately repair the broken or damaged portions. Replace sections that have lost their waterproof qualities.

If burlap and/or polyethylene film is temporarily removed for any reason during the curing period, soaker hoses shall be used to ensure that the entire exposed area is kept continuously wet. Saturated burlap and polyethylene film shall be replaced, resuming the specified curing conditions, as soon as possible.

Inspect the concrete surface once every 6 hours for the entirety of the 14 day curing period, so that all areas remain wet for the entire curing period and all curing requirements are satisfied.

Documentation. Provide the Engineer with a daily inspection set that includes:

- documentation that identifies any deficiencies found (including location of deficiency);
- documentation of corrective measures taken;
- a statement of certification that all areas are wet and all curing material is in place on the entire bridge deck;
- documentation showing the time and date of all inspections and the inspector's signature.
- documentation of any temporary removal of curing materials including location, date and time, length of time curing was removed, and means taken to ensure exposed area was kept continuously wet.

Cold Weather Curing. When concrete is being placed in cold weather, do so in accordance with the requirements in **Special Provision 90P-5095**.

When concrete is being placed and the ambient air temperature may be expected to drop below 40ºF (5ºC) during the curing period or when the ambient air temperature is expected to drop more than 25°F (14°C) below the temperature of the concrete during the first 24 hours after placement, provide suitable measures such as straw, additional burlap, or other suitable blanketing materials, and/or housing and artificial heat to maintain the concrete and girder temperatures between 55ºF (13ºC) and 75ºF (24ºC) as measured on the upper and lower surfaces of the concrete. Enclose the area underneath the deck and heat so that the temperature of the surrounding air is as close as possible to the temperature of concrete and between 55ºF (13ºC) and 75ºF (24ºC). Maintain wet burlap and polyethylene cover during the entire 14 day curing period. After the completion of the required curing period, remove the curing and protection so that the temperature of the concrete during the first 24 hours does not fall more than 25°F (14°C).

Curing Membrane. At the end of the 14-day curing period remove the wet burlap and polyethylene and within 30 minutes, apply two coats of curing membrane to the concrete. Apply the curing membrane when no free water remains on the surface but while the surface is still wet. The application rate of each coat of curing membrane is as prescribed by the manufacturer with a minimum spreading rate per coat of one liter per six square meters of concrete surface. If the concrete is dry or becomes dry, thoroughly wet it with water applied as a fog spray by means of approved equipment. Spray the second coat immediately after and at right angles to the first application.

Protect the curing membrane against marring for a period of at least 7 days. Give any marred or otherwise disturbed membrane an additional coating. Should the curing membrane be subjected to continuous injury, the Engineer may require wet burlap, polyethylene sheeting or other approved impermeable material to be applied at once.

Construction loads on the new one-course deck are subject to these limitations:

- Only foot traffic is allowed on the one-course deck during the 14-day curing period. Work to place reinforcing steel or forms for the bridge rail or barrier on the bridge deck is allowed 3 days after the concrete is placed, provided the curing is maintained on any exposed deck by keeping it wet during the 14-day curing period.
- Legal loads are allowed on the one-course deck 14 days after the concrete is placed.
- If the Engineer approves, heavy stationary loads (such as material stockpiles) may be allowed on the one-course deck 14 days after the concrete is placed. The Contractor must submit, to the Engineer for consideration, the weight of the material and the footprint pressure of the load.
- If the Engineer approves, vehicle loads greater than legal loads may be allowed on the bridge deck 28 days after the deck pour is completed. The Contractor must submit, to the Engineer for consideration, the axle (or track) spacing and width, the size of each tire (or track length and width) and their weight.
- The use of equipment which causes vibration will only be allowed to be used under the supervision of the Engineer.

Subsection 701.03, Add this subsection:

Qualification Slab

For each (LC-HPC) concrete bridge deck, construct a qualification slab with the dimensions shown in the Contract Documents to demonstrate the ability to handle, place, finish and cure the (LC-HPC) concrete bridge deck.

After the qualification batch complies with the requirements of **Special Provision 90P-5095,** construct a qualification slab 15 to 45 days prior to placing concrete in the bridge deck. Construct the qualification slab so that it complies with the details of the Contract Documents using the same concrete that is to be placed in the deck and was approved in the qualification batch. Submit the location of the qualification slab for approval by the Engineer. Place, finish, and cure as required by the contract documents using the same personnel, methods and equipment that the Contractor intends to use on the bridge deck. The Engineer will determine the air void characteristics using the Air Void Analyzer (AVA) in accordance with Special Provision 90M/P-156 (latest revision). Acceptance of the qualification slab is contingent upon demonstrating that the requirements of this specification are satisfied for placement, consolidation, finishing, and curing.

Not less than one day after construction of the qualification slab, core 4 full-depth 4 inch (100 mm) diameter cores, one from each quadrant of the qualification slab, and forward them to the Engineer for visual inspection of degree of consolidation.

Do not commence placement of (LC-HPC) concrete in the deck until permission is given by the KDOT Bureau of Materials and Research. Permission to place will be based on the Contractor's ability to adequately place, finish, and cure the concrete and on verification by the Engineer that adequate consolidation was achieved. Granting of permission to place concrete will be given or denied within 24 hours of receiving the cores from the Contractor, and is not contingent on the results of the air parameter test. If an additional qualification slab is deemed necessary by the Engineer, it will be paid for at the contract unit price for Qualification Slab.

Grinding and Grooving

For (LC-HPC) concrete, perform grinding on hardened concrete for the entire deck surface after the curing period to achieve a plane surface and grooving of the final wearing surface as shown in the Contract Documents. Surface variations shall not exceed 1/8 inch (3 mm) in 10 feet (3 m) as measured using an approved profiling device, or other methods approved by the Engineer after the curing period.

Use a self-propelled grinding machine with diamond blades mounted on a multi-blade arbor. Avoid using equipment that causes excessive ravels, aggregate fractures, or spalls. Use vacuum equipment or other continuous methods to remove grinding slurry and residue.

Once the grinding has been achieved, give the surface a suitable texture by transverse grooving. Use diamond blades mounted on a self-propelled machine that is designed for texturing pavement. Grooving of the finished surface may be done with equipment that is not self-propelled providing that the contractor can show proficiency with the equipment. Use equipment that does not cause strain, excessive raveling, aggregate fracture, spalls, disturbance of the transverse or longitudinal joint, or damage to the existing concrete surface. Make the grooving approximately 3/16 inch (5 mm) in width at 3/4 inch (20 mm) centers and the groove depth approximately 1/8 inch (3 mm). For bridges with drains, the transverse grooving should terminate approximately 2 feet (0.6 m) in from the gutter line at the base of the curb. Continuously remove all slurry residue resulting from the texturing operation.

Post-Construction Conference.

At the completion of the deck placement, curing, grinding and grooving for a bridge using (LC-HPC) concrete, a post-construction conference will be held with all parties that participated in the planning and construction present. All problems and successes for the project shall be discussed and recorded by the Engineer at this meeting.

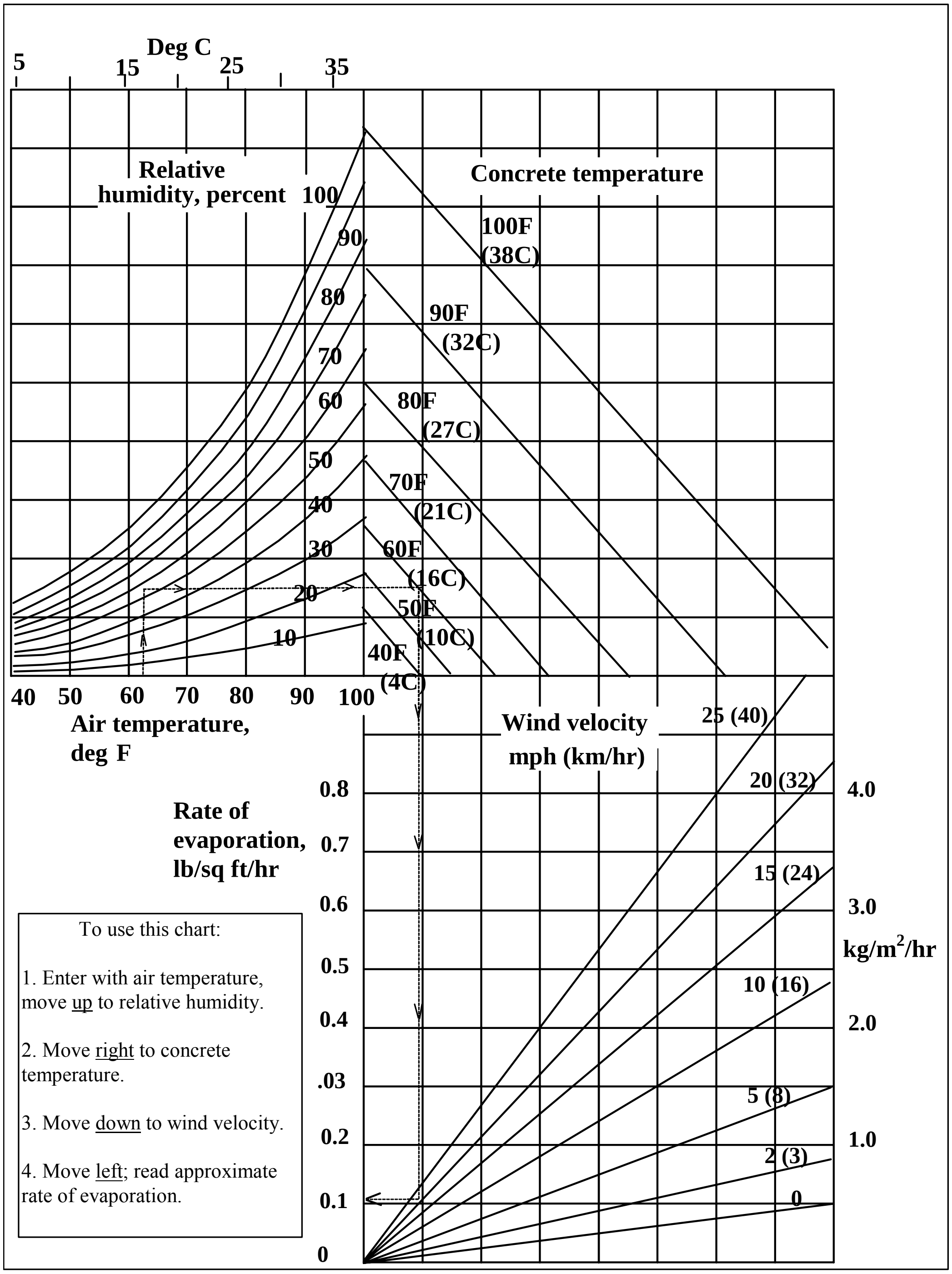
4.0 MEASUREMENT AND PAYMENT.

Grade * (AE)(LC-HPC) Concrete will measure the by the cubic yard (cubic meter), Qualification Slab by the cubic yard (cubic meter). Measurement will be on the neat lines of the structure as shown on the Plans. No deductions are made for reinforcing steel and pile heads extending into the concrete.

Payment for "Grade * (AE)(LC-HPC)" and “Qualification Slab” at the Contract unit price is full compensation for the specified work.

10-31-06 BD (BS)(SK)
5097

STANDARD PRACTICE FOR CURING CONCRETE



Effect of concrete and air temperatures, relative humidity, and wind velocity on the rate of evaporation of surface moisture from concrete. This chart provides a graphic method of estimating the loss of surface moisture for various weather conditions. To use the chart, follow the four steps outlined above. When the evaporation rate exceeds 0.2 lb/ft^2/hr (1.0 kg/ m^2/hr), measures shall be taken to prevent excessive moisture loss from the surface of unhardened concrete; when the rate is less than 0.2 lb/ft^2/hr (1.0 kg/ m^2/hr) such measures may be needed. When excessive moisture loss is not prevented, plastic cracking is likely to occur.

KANSAS DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION TO THE
STANDARD SPECIFICATIONS, 1990 EDITION

NOTE: This special provision is generally written in the imperative mood. The subject, "the *Contractor*" is implied. Also implied in this language are "*shall*", "*shall be*", or similar words and phrases. The word "*will*" generally pertains to decisions or actions of the Kansas Department of Transportation.

LOW CRACKING – HIGH PERFORMANCE CONCRETE (LC-HPC) CONSTRUCTION

1.0 DESCRIPTION.

Construct the concrete bridge deck designated in the Contract Documents that complies with Section 701 and this Special Provision.

BID ITEMS	**UNIT**
Concrete Grade * (AE)(LC-HPC) * Grade of Concrete	Cubic yard (cubic meter)
Qualification Slab	Cubic yard (cubic meter)

2.0 MATERIALS.

Concrete ....**Special Provision 90M-7360**

Concrete Curing Materials ....**SECTION 1400**

3.0 CONSTRUCTION REQUIREMENTS.

Subsection 701.03(e). Delete the second paragraph of this subsection and replace with the following:

For placement limitations refer to **Special Provision 90M-7360.**

Fog all bridge deck placements. Begin the fogging immediately behind the finishing operations. Maintain the fogging to produce a “gloss to semi-gloss water sheen” on the surface until the curing is applied. Apply the fog over the entire placement width. Reduce fogging only if excess water accumulates on the surface and begins to run off. Do not use accumulated water from fogging as a finishing aid. Do not allow water to drip, flow or puddle on the concrete surface during fogging, placement of absorptive material, or at any time before the concrete has achieved final set.

Produce a fog spray from nozzles that atomize the droplets capable of keeping a large surface area damp without depositing excess water. Use high pressure equipment that generates at least 1200 psi at 2.2 gpm (8.3 MPa at 8.3 L/minute), or low pressure equipment having nozzles capable of supplying a maximum flow rate of 1.6 gpm (6.1 L/minute). Mount the fogging equipment on finishing equipment or other equipment that may immediately follow the finishing equipment. Use hand-held fogging apparatus for the concrete under the finishing equipment that is not reachable by mounted fogging equipment, for corners not covered by machine fogging, and for all exposed concrete in the event that advancement of the finishing equipment is delayed.

Maintain environmental conditions and concrete temperature such that the evaporation rate is less than 0.2 lb/sq ft/hr (1.0 kg/sq m/hr). For LC-HPC concrete, the temperature of the mixed concrete immediately before placement must be at least 55°F (13ºC), but not more than 70°F (21ºC). With approval by the engineer, the temperature of the concrete may be adjusted 5°F (3ºC) above or below this range. The effects of the required continuous fogging will not be considered in the estimation of the evaporation rate. This may require placing the deck at night, in the early morning or on another day. The evaporation rate (as determined in the American Concrete Institute Manual of Concrete Practice 305R, Chapter 2) is a function of air temperature, concrete temperature, wind speed, and humidity.

Just prior to and at least once per hour during placement of the concrete, measure and record the air temperature, concrete temperature, wind speed, and humidity. Take the air temperature, wind and humidity measurements approximately 12 inches (300 mm) above the surface of the deck. With this information, determine the evaporation rate by using the KDOT supplied software or by using Figure 2.1.5 from the above reference (copy attached). When the evaporation rate is equal to or above 0.2 lb/sq ft/hr (1.0 kg/sq m/hr), take measures (such as installing wind breaks, cooling the concrete, sun screens etc.) to create and maintain an evaporation rate less than 0.2 lb/sq ft/hr (1.0 kg/sq m/hr) on the entire bridge deck.

During the preconstruction conference, submit an acceptable Quality Control Plan detailing the equipment (for both determining and controlling the evaporation rate and concrete temperature) and procedures used to minimize the evaporation rate. Follow the same Contractor's Concrete Structures Quality Control Plan as outlined in KDOT's Construction Manual, Part V.

Subsection 701.03(e). Delete the ninth paragraph of this subsection and replace with the following:

Place concrete by conveyor belt or concrete bucket. Pumping of LC-HPC will be allowed if the contractor can show proficiency when placing the approved mix during construction of the qualification slab. Placement by pump will also be allowed with prior approval of the Engineer contingent upon successful placement by pump of the approved mix at least 15 days prior to placing concrete in the bridge deck.

Subsection 701.03(g). Delete this subsection and add the following:

Strike the bridge deck off with a vibrating screed or single-drum roller screed. Finish the surface by a burlap drag or metal pan mounted to the finishing equipment. Use a float or other approved device behind the burlap drag or metal plan to remove any local irregularities. The finisher may be self-propelled or it may be propelled by manually operated winches. The screed must be self-oscillating and it may operate or finish from a position transverse or longitudinal to the bridge roadway centerline. Prior to commencing concreting operations, position the finisher throughout the proposed placement area, as directed by the Engineer, to permit verification of the reinforcing steel positioning. Irregular sections may be finished by other methods approved by the Engineer.

The addition of water or precure/finishing aid to the surface of concrete to assist in finishing operations is prohibited.

Tining of plastic concrete is prohibited on (LC-HPC) concrete. All concrete surfaces must be reasonably true and even, free from stone pockets, excessive depressions or projections beyond the surface.

Subsection 701.03(h). Delete this subsection and replace with the following:

Cure all newly placed concrete immediately after finishing, and continue uninterrupted for at least 14 days. Cure by the <u>Water Method With Waterproof Cover</u> as described below. Cure all pedestrian walkway surfaces in the same manner as the bridge deck. Cure barriers in the same manner as the bridge deck, except fogging is not required for the barriers. Curing compounds are prohibited during the 14 day curing period.

<u>Water With Waterproof Cover</u>

Apply 1 layer of wet burlap within 10 minutes of concrete strike-off followed by a second layer of wet burlap within 5 minutes. Do not allow the surface to dry after the strike-off, or at any time during the cure period.

Maintain the wet burlap in a fully wet condition using misting hoses, self-propelled, machine-mounted fogging equipment with effective fogging area spanning the deck width moving continuously across the entire burlap-covered surface, or other approved devices until the concrete has set sufficiently to allow foot traffic. At that time, place soaker hoses on the burlap, and supply running water continuously to maintain continuous saturation of all burlap material to the entire concrete surface.

Place white polyethylene film on top of the soaker hoses covering the entire concrete surface after soaker hoses have been placed, but not more than 12 hours after the placement of the (LC-HPC) Concrete. Use sheets of the widest practical width and overlap adjacent sheets a minimum of 6 inches (150 mm) and tightly sealed with pressure sensitive tape, mastic, glue, or other approved methods to form a complete waterproof cover of the entire concrete surface. Secure the polyethylene film so that wind will not displace it. Should any portion of the sheets be broken or damaged before expiration of the curing period, immediately repair the broken or damaged portions. Replace sections that have lost their waterproof qualities.

If burlap and/or polyethylene film is temporarily removed for any reason during the curing period, soaker hoses shall be used to ensure that the entire exposed area is kept continuously wet. Saturated burlap and polyethylene film shall be replaced, resuming the specified curing conditions, as soon as possible.

Inspect the concrete surface once every 6 hours for the entirety of the 14 day curing period, so that all areas remain wet for the entire curing period and all curing requirements are satisfied.

Documentation. Provide the Engineer with a daily inspection set that includes:

- documentation that identifies any deficiencies found (including location of deficiency);
- documentation of corrective measures taken;
- a statement of certification that all areas are wet and all curing material is in place on the entire bridge deck;
- documentation showing the time and date of all inspections and the inspector's signature.
- documentation of any temporary removal of curing materials including location, date and time, length of time curing was removed, and means taken to ensure exposed area was kept continuously wet.

Cold Weather Curing. When concrete is being placed in cold weather, do so in accordance with the requirements in **Special Provision 90M-7360**.

When concrete is being placed and the ambient air temperature may be expected to drop below 40ºF (5ºC) during the curing period or when the ambient air temperature is expected to drop more than 25°F (14°C) below the temperature of the concrete during the first 24 hours after placement, provide suitable measures such as straw, additional burlap, or other suitable blanketing materials, and/or housing and artificial heat to maintain the concrete and girder temperatures between 55ºF (13ºC) and 75ºF (24ºC) as measured on the upper and lower surfaces of the concrete. Enclose the area underneath the deck and heat so that the temperature of the surrounding air is as close as possible to the temperature of concrete and between 55ºF (13ºC) and 75ºF (24ºC). Maintain wet burlap and polyethylene cover during the entire 14 day curing period. After the completion of the required curing period, remove the curing and protection so that the temperature of the concrete during the first 24 hours does not fall more than 25°F (14°C).

Curing Membrane. At the end of the 14-day curing period remove the wet burlap and polyethylene and within 30 minutes, apply two coats of curing membrane to the concrete. Apply the curing membrane when no free water remains on the surface but while the surface is still wet. The application rate of each coat of curing membrane is as prescribed by the manufacturer with a minimum spreading rate per coat of one liter per six square meters of concrete surface. If the concrete is dry or becomes dry, thoroughly wet it with water applied as a fog spray by means of approved equipment. Spray the second coat immediately after and at right angles to the first application.

Protect the curing membrane against marring for a period of at least 7 days. Give any marred or otherwise disturbed membrane an additional coating. Should the curing membrane be subjected to continuous injury, the Engineer may require wet burlap, polyethylene sheeting or other approved impermeable material to be applied at once.

Construction loads on the new one-course deck are subject to these limitations:

- Only foot traffic is allowed on the one-course deck during the 14-day curing period. Work to place reinforcing steel or forms for the bridge rail or barrier on the bridge deck is allowed 3 days after the concrete is placed, provided the curing is maintained on any exposed deck by keeping it wet during the 14-day curing period.
- Legal loads are allowed on the one-course deck 14 days after the concrete is placed.
- If the Engineer approves, heavy stationary loads (such as material stockpiles) may be allowed on the one-course deck 14 days after the concrete is placed. The Contractor must submit, to the Engineer for consideration, the weight of the material and the footprint pressure of the load.
- If the Engineer approves, vehicle loads greater than legal loads may be allowed on the bridge deck 28 days after the deck pour is completed. The Contractor must submit, to the Engineer for consideration, the axle (or track) spacing and width, the size of each tire (or track length and width) and their weight.
- The use of equipment which causes vibration will only be allowed to be used under the supervision of the Engineer.

Subsection 701.03, Add this subsection:

Qualification Slab

For each (LC-HPC) concrete bridge deck, construct a qualification slab with the dimensions shown in the Contract Documents to demonstrate the ability to handle, place, finish and cure the (LC-HPC) concrete bridge deck.

After the qualification batch complies with the requirements of **Special Provision 90M-7360,** construct a qualification slab 15 to 45 days prior to placing concrete in the bridge deck. Construct the qualification slab so that it complies with the details of the Contract Documents using the same concrete that is to be placed in the deck and was approved in the qualification batch. Submit the location of the qualification slab for approval by the Engineer. Place, finish, and cure as required by the contract documents using the same personnel, methods and equipment that the Contractor intends to use on the bridge deck. The Engineer will determine the air void characteristics using the Air Void Analyzer (AVA) in accordance with Special Provision 90M/P-156 (latest revision). Acceptance of the qualification slab is contingent upon demonstrating that the requirements of this specification are satisfied for placement, consolidation, finishing, and curing.

Not less than one day after construction of the qualification slab, core 4 full-depth 4 inch (100 mm) diameter cores, one from each quadrant of the qualification slab, and forward them to the Engineer for visual inspection of degree of consolidation.

Do not commence placement of (LC-HPC) concrete in the deck until permission is given by the KDOT Bureau of Materials and Research. Permission to place will be based on the Contractor's ability to adequately place, finish, and cure the concrete and on verification by the Engineer that adequate consolidation was achieved. Granting of permission to place concrete will be given or denied within 24 hours of receiving the cores from the Contractor, and is not contingent on the results of the air parameter test. If an additional qualification slab is deemed necessary by the Engineer, it will be paid for at the contract unit price for Qualification Slab.

Grinding and Grooving

For (LC-HPC) concrete, perform grinding on hardened concrete for the entire deck surface after the curing period to achieve a plane surface and grooving of the final wearing surface as shown in the Contract Documents. Surface variations shall not exceed 1/8 inch (3 mm) in 10 feet (3 m) as measured using an approved profiling device, or other methods approved by the Engineer after the curing period.

Use a self-propelled grinding machine with diamond blades mounted on a multi-blade arbor. Avoid using equipment that causes excessive ravels, aggregate fractures, or spalls. Use vacuum equipment or other continuous methods to remove grinding slurry and residue.

Once the grinding has been achieved, give the surface a suitable texture by transverse grooving. Use diamond blades mounted on a self-propelled machine that is designed for texturing pavement. Grooving of the finished surface may be done with equipment that is not self-propelled providing that the contractor can show proficiency with the equipment. Use equipment that does not cause strain, excessive raveling, aggregate fracture, spalls, disturbance of the transverse or longitudinal joint, or damage to the existing concrete surface. Make the grooving approximately 3/16 inch (5 mm) in width at 3/4 inch (20 mm) centers and the groove depth approximately 1/8 inch (3 mm). For bridges with drains, the transverse grooving should terminate approximately 2 feet (0.6 m) in from the gutter line at the base of the curb. Continuously remove all slurry residue resulting from the texturing operation.

Post-Construction Conference.

At the completion of the deck placement, curing, grinding and grooving for a bridge using (LC-HPC) concrete, a post-construction conference will be held with all parties that participated in the planning and construction present. All problems and successes for the project shall be discussed and recorded by the Engineer at this meeting.

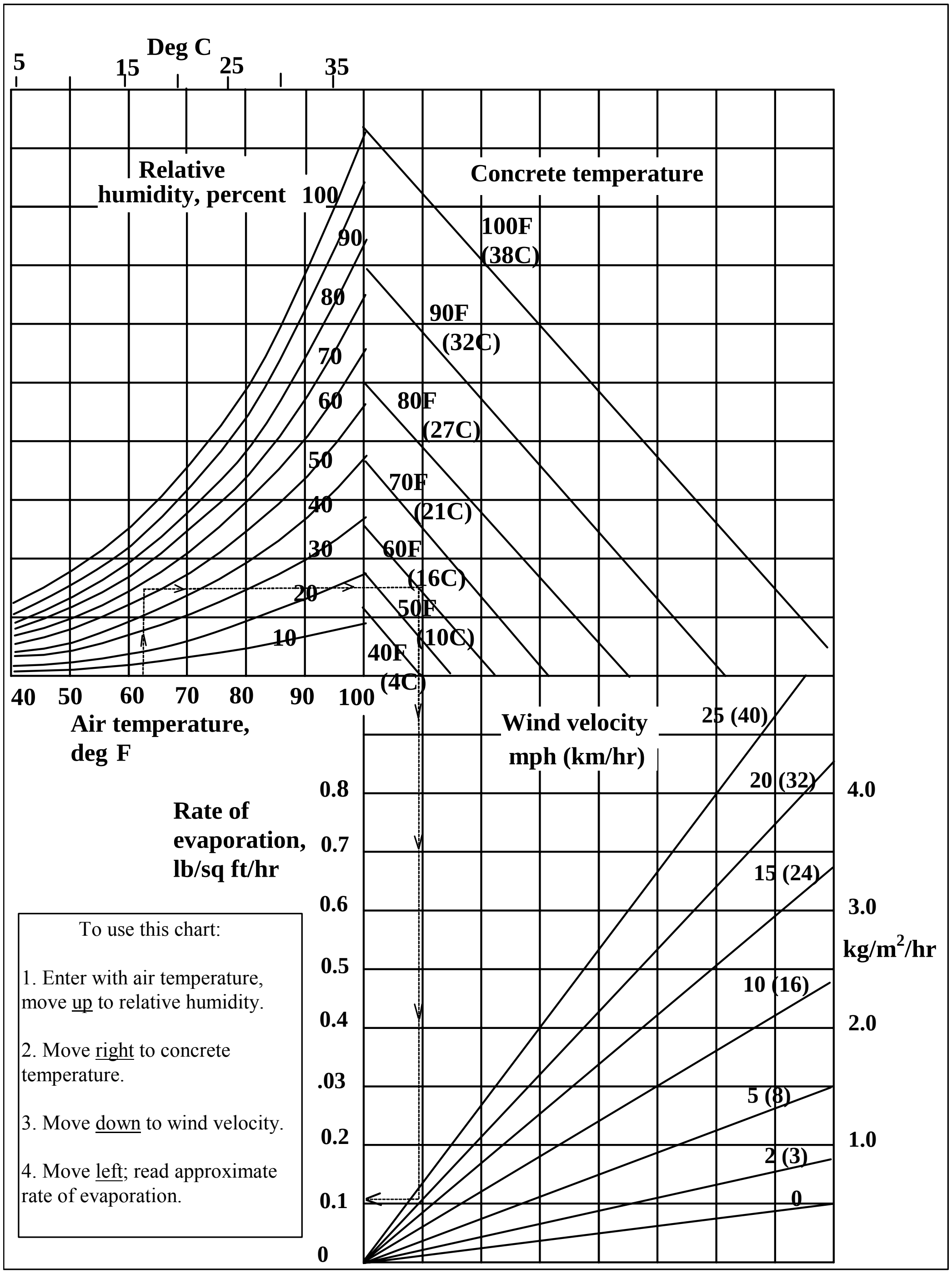
4.0 MEASUREMENT AND PAYMENT.

Grade * (AE)(LC-HPC) Concrete will measure the by the cubic yard (cubic meter), Qualification Slab by the cubic yard (cubic meter). Measurement will be on the neat lines of the structure as shown on the Plans. No deductions are made for reinforcing steel and pile heads extending into the concrete.

Payment for "Grade * (AE)(LC-HPC)" and “Qualification Slab” at the Contract unit price is full compensation for the specified work.

10-31-06 BD (BS)(SK)
7361

STANDARD PRACTICE FOR CURING CONCRETE



Effect of concrete and air temperatures, relative humidity, and wind velocity on the rate of evaporation of surface moisture from concrete. This chart provides a graphic method of estimating the loss of surface moisture for various weather conditions. To use the chart, follow the four steps outlined above. When the evaporation rate exceeds 0.2 lb/ft^2/hr (1.0 kg/ m^2/hr), measures shall be taken to prevent excessive moisture loss from the surface of unhardened concrete; when the rate is less than 0.2 lb/ft^2/hr (1.0 kg/ m^2/hr) such measures may be needed. When excessive moisture loss is not prevented, plastic cracking is likely to occur.

LCHPC-3 LOW CRACKING – HIGH PERFORMANCE CONCRETE (LC-HPC) CONSTRUCTION

LCHPC-3.1 DESCRIPTION.

Construct the concrete bridge deck designated in the Contract Documents that complies with Section 701 and this Special Provision.

BID ITEMS	UNIT
Concrete Grade * (AE)(LC-HPC) * Grade of Concrete	Cubic yard (cubic meter)
Qualification Slab	Cubic yard (cubic meter)

LCHPC-3.2 MATERIALS.

Concrete..**LCHPC-1**
Concrete Curing Materials .... **SECTION 1400**

LCHPC-3.3 CONSTRUCTION REQUIREMENTS.

Subsection 701.03(e). Delete the second paragraph of this subsection and replace with the following:

For placement limitations refer to **LCHPC-1.**

Fog all bridge deck placements. Begin the fogging immediately behind the finishing operations. Maintain the fogging to produce a "gloss to semi-gloss water sheen" on the surface until the curing is applied. Apply the fog over the entire placement width. Reduce fogging only if excess water accumulates on the surface and begins to run off. Do not use accumulated water from fogging as a finishing aid. Do not allow water to drip, flow or puddle on the concrete surface during fogging, placement of absorptive material, or at any time before the concrete has achieved final set.

Produce a fog spray from nozzles that atomize the droplets capable of keeping a large surface area damp without depositing excess water. Use high pressure equipment that generates at least 1200 psi at 2.2 gpm (8.3 MPa at 8.3 L/minute), or low pressure equipment having nozzles capable of supplying a maximum flow rate of 1.6 gpm (6.1 L/minute). Mount the fogging equipment on finishing equipment or other equipment that may immediately follow the finishing equipment. Use hand-held fogging apparatus for the concrete under the finishing equipment that is not reachable by mounted fogging equipment, for corners not covered by machine fogging, and for all exposed concrete in the event that advancement of the finishing equipment is delayed.

Maintain environmental conditions and concrete temperature such that the evaporation rate is less than 0.2 lb/sq ft/hr (1.0 kg/sq m/hr). For LC-HPC concrete, the temperature of the mixed concrete immediately before placement must be at least 55°F (13°C), but not more than 70°F (21°C). With approval by the engineer, the temperature of the concrete may be adjusted 5°F (3°C) above or below this range. The effects of the required continuous fogging will not be considered in the estimation of the evaporation rate. This may require placing the deck at night, in the early morning or on another day. The evaporation rate (as determined in the American Concrete Institute Manual of Concrete Practice 305R, Chapter 2) is a function of air temperature, concrete temperature, wind speed, and humidity.

Just prior to and at least once per hour during placement of the concrete, measure and record the air temperature, concrete temperature, wind speed, and humidity. Take the air temperature, wind and humidity measurements approximately 12 inches (300 mm) above the surface of the deck. With this information, determine the evaporation rate by using the KDOT supplied software or by using Figure 2.1.5 from the above reference (copy attached). When the evaporation rate is equal to or above 0.2 lb/sq ft/hr (1.0 kg/sq m/hr), take measures (such as installing wind breaks, cooling the concrete, sun screens etc.) to create and maintain an evaporation rate less than 0.2 lb/sq ft/hr (1.0 kg/sq m/hr) on the entire bridge deck.

During the preconstruction conference, submit an acceptable Quality Control Plan detailing the equipment (for both determining and controlling the evaporation rate and concrete temperature) and procedures used to minimize the evaporation rate. Follow the same Contractor's Concrete Structures Quality Control Plan as outlined in KDOT's Construction Manual, Part V.

Subsection 701.03(e). Delete the ninth paragraph of this subsection and replace with the following:

Place concrete by conveyor belt or concrete bucket. Pumping of LC-HPC will be allowed if the contractor can show proficiency when placing the approved mix during construction of the qualification slab. Placement by pump will also be allowed with prior approval of the Engineer contingent upon successful placement by pump of the approved mix at least 15 days prior to placing concrete in the bridge deck.

Subsection 701.03(g). Delete this subsection and add the following:

Strike the bridge deck off with a vibrating screed or single-drum roller screed. Finish the surface by a burlap drag or metal pan mounted to the finishing equipment. Use a float or other approved device behind the burlap drag or metal plan to remove any local irregularities. The finisher may be self-propelled or it may be propelled by manually operated winches. The screed must be self-oscillating and it may operate or finish from a position transverse or longitudinal to the bridge roadway centerline. Prior to commencing concreting operations, position the finisher throughout the proposed placement area, as directed by the Engineer, to permit verification of the reinforcing steel positioning. Irregular sections may be finished by other methods approved by the Engineer.

The addition of water or precure/finishing aid to the surface of concrete to assist in finishing operations is prohibited.

Tining of plastic concrete is prohibited on (LC-HPC) concrete. All concrete surfaces must be reasonably true and even, free from stone pockets, excessive depressions or projections beyond the surface.

Subsection 701.03(h). Delete this subsection and replace with the following:

Cure all newly placed concrete immediately after finishing, and continue uninterrupted for at least 14 days. Cure by the Water Method With Waterproof Cover as described below. Cure all pedestrian walkway surfaces in the same manner as the bridge deck. Cure barriers in the same manner as the bridge deck, except fogging is not required for the barriers. Curing compounds are prohibited during the 14 day curing period.

Water With Waterproof Cover

Apply 1 layer of wet burlap within 10 minutes of concrete strike-off followed by a second layer of wet burlap within 5 minutes. Do not allow the surface to dry after the strike-off, or at any time during the cure period.

Maintain the wet burlap in a fully wet condition using misting hoses, self-propelled, machine-mounted fogging equipment with effective fogging area spanning the deck width moving continuously across the entire burlap-covered surface, or other approved devices until the concrete has set sufficiently to allow foot traffic. At that time, place soaker hoses on the burlap, and supply running water continuously to maintain continuous saturation of all burlap material to the entire concrete surface.

Place white polyethylene film on top of the soaker hoses covering the entire concrete surface after soaker hoses have been placed, but not more than 12 hours after the placement of the (LC-HPC) Concrete. Use sheets of the widest practical width and overlap adjacent sheets a minimum of 6 inches (150 mm) and tightly sealed with pressure sensitive tape, mastic, glue, or other approved methods to form a complete waterproof cover of the entire concrete surface. Secure the polyethylene film so that wind will not displace it. Should any portion of the sheets be broken or damaged before expiration of the curing period, immediately repair the broken or damaged portions. Replace sections that have lost their waterproof qualities.

If burlap and/or polyethylene film is temporarily removed for any reason during the curing period, soaker hoses shall be used to ensure that the entire exposed area is kept continuously wet. Saturated burlap and polyethylene film shall be replaced, resuming the specified curing conditions, as soon as possible.

Inspect the concrete surface once every 6 hours for the entirety of the 14 day curing period, so that all areas remain wet for the entire curing period and all curing requirements are satisfied.

Documentation. Provide the Engineer with a daily inspection set that includes:

- documentation that identifies any deficiencies found (including location of deficiency);
- documentation of corrective measures taken;
- a statement of certification that all areas are wet and all curing material is in place on the entire bridge deck;
- documentation showing the time and date of all inspections and the inspector's signature.
- documentation of any temporary removal of curing materials including location, date and time, length of time curing was removed, and means taken to ensure exposed area was kept continuously wet.

Cold Weather Curing. When concrete is being placed in cold weather, do so in accordance with the requirements in **LCHPC-1.**

When concrete is being placed and the ambient air temperature may be expected to drop below 40°F (5°C) during the curing period or when the ambient air temperature is expected to drop more than 25°F (14°C) below the temperature of the concrete during the first 24 hours after placement, provide suitable measures such as straw, additional burlap, or other suitable blanketing materials, and/or housing and artificial heat to maintain the concrete and girder temperatures between 55°F (13°C) and 75°F (24°C) as measured on the upper and lower surfaces of the concrete. Enclose the area underneath the deck and heat so that the temperature of the surrounding air is as close as possible to the temperature of concrete and between 55°F (13°C) and 75°F (24°C). Maintain wet burlap and polyethylene cover during the entire 14 day curing period. After the completion of the required curing period, remove the curing and protection so that the temperature of the concrete during the first 24 hours does not fall more than 25°F (14°C).

Curing Membrane. At the end of the 14-day curing period remove the wet burlap and polyethylene and within 30 minutes, apply two coats of curing membrane to the concrete. Apply the curing membrane when no free water remains on the surface but while the surface is still wet. The application rate of each coat of curing membrane is as prescribed by the manufacturer with a minimum spreading rate per coat of one liter per six square meters of concrete surface. If the concrete is dry or becomes dry, thoroughly wet it with water applied as a fog spray by means of approved equipment. Spray the second coat immediately after and at right angles to the first application.

Protect the curing membrane against marring for a period of at least 7 days. Give any marred or otherwise disturbed membrane an additional coating. Should the curing membrane be subjected to continuous injury, the Engineer may require wet burlap, polyethylene sheeting or other approved impermeable material to be applied at once.

Construction loads on the new one-course deck are subject to these limitations:

- Only foot traffic is allowed on the one-course deck during the 14-day curing period. Work to place reinforcing steel or forms for the bridge rail or barrier on the bridge deck is allowed 3 days after the concrete is placed, provided the curing is maintained on any exposed deck by keeping it wet during the 14-day curing period.
- Legal loads are allowed on the one-course deck 14 days after the concrete is placed.
- If the Engineer approves, heavy stationary loads (such as material stockpiles) may be allowed on the one-course deck 14 days after the concrete is placed. The Contractor must submit, to the Engineer for consideration, the weight of the material and the footprint pressure of the load.
- If the Engineer approves, vehicle loads greater than legal loads may be allowed on the bridge deck 28 days after the deck pour is completed. The Contractor must submit, to the Engineer for consideration, the axle (or track) spacing and width, the size of each tire (or track length and width) and their weight.
- The use of equipment which causes vibration will only be allowed to be used under the supervision of the Engineer.

Subsection 701.03, Add this subsection:

Qualification Slab

For each (LC-HPC) concrete bridge deck, construct a qualification slab with a length of 30 feet and a width of 40 feet to demonstrate the ability to handle, place, finish and cure the (LC-HPC) concrete bridge deck.

After the qualification batch complies with the requirements of **LCHPC-1,** construct a qualification slab 15 to 45 days prior to placing concrete in the bridge deck. Construct the qualification slab so that it complies with the details of the Contract Documents using the same concrete that is to be placed in the deck and was approved in the qualification batch. Submit the location of the qualification slab for approval by the Engineer. Place, finish, and cure as required by the contract documents using the same personnel, methods and equipment that the Contractor intends to use on the bridge deck. The Engineer may determine the air void characteristics using the Air Void Analyzer (AVA) in accordance with Special Provision 90M/P-156 (latest revision) or by other means. Acceptance of the qualification slab is contingent upon demonstrating that the requirements of this specification are satisfied for placement, consolidation, finishing, and curing.

Not less than one day after construction of the qualification slab, core 4 full-depth 4 inch (100 mm) diameter cores, one from each quadrant of the qualification slab, and forward them to the Engineer for visual inspection of degree of consolidation.

Do not commence placement of (LC-HPC) concrete in the deck until permission is given by the Engineer . Permission to place will be based on the Contractor's ability to adequately place, finish, and cure the concrete and on verification by the Engineer that adequate consolidation was achieved. Granting of permission to place concrete will be given or denied within 24 hours of receiving the cores from the Contractor, and is not contingent on the results of the air parameter test. If an additional qualification slab is deemed necessary by the Engineer, it will be paid for at the contract unit price for Qualification Slab.

Grinding and Grooving

For (LC-HPC) concrete, perform grinding on hardened concrete for the entire deck surface after the curing period to achieve a plane surface and grooving of the final wearing surface as shown in the Contract Documents. Surface variations shall not exceed 1/8 inch (3 mm) in 10 feet (3 m) as measured using an approved profiling device, or other methods approved by the Engineer after the curing period.

Use a self-propelled grinding machine with diamond blades mounted on a multi-blade arbor. Avoid using equipment that causes excessive ravels, aggregate fractures, or spalls. Use vacuum equipment or other continuous methods to remove grinding slurry and residue.

Once the grinding has been achieved, give the surface a suitable texture by transverse grooving. Use diamond blades mounted on a self-propelled machine that is designed for texturing pavement. Grooving of the finished surface may be done with equipment that is not self-propelled providing that the contractor can show proficiency with the equipment. Use equipment that does not cause strain, excessive raveling, aggregate fracture, spalls, disturbance of the transverse or longitudinal joint, or damage to the existing concrete surface. Make the grooving approximately 3/16 inch (5 mm) in width at 3/4 inch (20 mm) centers and the groove depth approximately 1/8 inch (3 mm). For bridges with drains, the transverse grooving should terminate approximately 2 feet (0.6 m) in from the gutter line at the base of the curb. Continuously remove all slurry residue resulting from the texturing operation.

Post-Construction Conference.

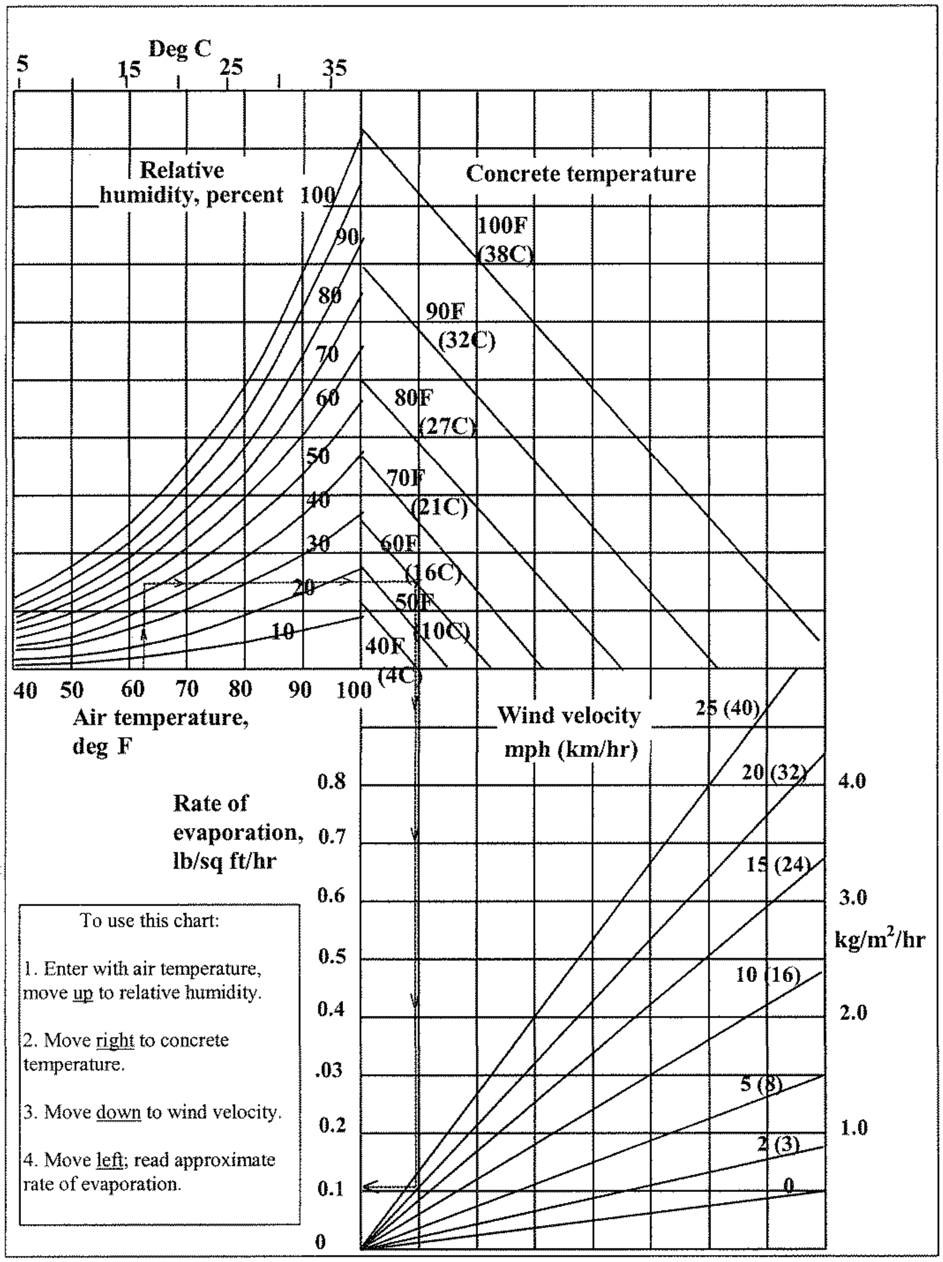
At the completion of the deck placement, curing, grinding and grooving for a bridge using (LC-HPC) concrete, a post-construction conference will be held with all parties that participated in the planning and construction present. All problems and successes for the project shall be discussed and recorded by the Engineer at this meeting.

LCHPC-3.4 MEASUREMENT AND PAYMENT.

Grade * (AE)(LC-HPC) Concrete will measure the by the cubic yard (cubic meter), Qualification Slab by the cubic yard (cubic meter). Measurement will be on the neat lines of the structure as shown on the Plans. No deductions are made for reinforcing steel and pile heads extending into the concrete.

Payment for "Grade * (AE)(LC-HPC)" and "Qualification Slab" at the Contract unit price is full compensation for the specified work.

STANDARD PRACTICE FOR CURING CONCRETE



Effect of concrete and air temperatures, relative humidity, and wind velocity on the rate of evaporation of surface moisture from concrete. This chart provides a graphic method of estimating the loss of surface moisture for various weather conditions. To use the chart, follow the four steps outlined above. When the evaporation rate exceeds 0.2 lb/ft^2/hr (1.0 kg/ m^2/hr), measures shall be taken to prevent excessive moisture loss from the surface of unhardened concrete; when the rate is less than 0.2 lb/ft^2/hr (1.0 kg/ m^2/hr) such measures may be needed. When excessive moisture loss is not prevented, plastic cracking is likely to occur.

KANSAS DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION TO THE
STANDARD SPECIFICATIONS, 2007 EDITION

Add a new SECTION to DIVISION 700:

LOW-CRACKING HIGH-PERFORMANCE CONCRETE – CONSTRUCTION

1.0 DESCRIPTION

Construct the low-cracking high-performance concrete (LC-HPC) structures according to the Contract Documents and this specification.

BID ITEMS	UNITS
Qualification Slab	Cubic Yard
Concrete (*) (AE) (LC-HPC)	Cubic Yard

*Grade of Concrete

2.0 MATERIALS

Provide materials that comply with the applicable requirements.

LC-HPC .... **07-PS0166, latest version**

Concrete Curing Materials .... **DIVISION 1400**

3.0 CONSTRUCTION REQUIREMENTS

a. Qualification Batch and Slab. For each LC-HPC bridge deck, produce a qualification batch of LC-HPC that is to be placed in the deck and complies with **07-PS0166, latest version**, and construct a qualification slab that complies with this specification to demonstrate the ability to handle, place, finish and cure the LC-HPC bridge deck.

After the qualification batch of LC-HPC complies with **07-PS0166, latest version**, construct a qualification slab 15 to 45 days prior to placing LC-HPC in the bridge deck. Construct the qualification slab to comply with the Contract Documents, using the same LC-HPC that is to be placed in the deck and that was approved in the qualification batch. Submit the location of the qualification slab for approval by the Engineer. Place, finish and cure the qualification slab according to the Contract Documents, using the same personnel, methods and equipment (including the concrete pump, if used) that will be used on the bridge deck.

A minimum of 1 day after construction of the qualification slab, core 4 full-depth 4 inch diameter cores, one from each quadrant of the qualification slab, and forward them to the Engineer for visual inspection of degree of consolidation.

Do not commence placement of LC-HPC in the deck until approval is given by the Engineer. Approval to place concrete on the deck will be based on satisfactory placement, consolidation, finishing and curing of the qualification slab and cores, and will be given or denied within 24 hours of receiving the cores from the Contractor. If an additional qualification slab is deemed necessary by the Engineer, it will be paid for at the contract unit price for Qualification Slab.

b. Falsework and Forms. Construct falsework and forms according to **SECTION 708**.

c. Handling and Placing LC-HPC.

(1) Quality Control Plan (QCP). At a project progress meeting prior to placing LC-HPC, discuss with the Engineer the method and equipment used for deck placement. Submit an acceptable QCP according to the Contractor's Concrete Structures Quality Control Plan, Part V. Detail the equipment (for both determining and controlling the evaporation rate and LC-HPC temperature), procedures used to minimize the evaporation rate, plans for maintaining a continuous rate of finishing the deck without delaying the application of curing materials within the time specified in **subsection 3.0f.**, including maintaining a continuous supply of LC-HPC throughout the placement with an adequate quantity of LC-HPC to complete the deck and filling diaphragms and end walls in advance of deck placement, and plans for placing the curing materials within the time specified in **subsection 3.0f**. In the plan, also include input from the LC-HPC supplier as to how variations in the moisture content of the aggregate will be handled, should they occur during construction.

(2) Use a method and sequence of placing LC-HPC approved by the Engineer. Do not place LC-HPC until the forms and reinforcing steel have been checked and approved. Before placing LC-HPC, clean all forms of debris.

(3) Finishing Machine Setup. On bridges skewed greater than 10º, place LC-HPC on the deck forms across the deck on the same skew as the bridge, unless approved otherwise by State Bridge Office (SBO). Operate the bridge deck finishing machine on the same skew as the bridge, unless approved otherwise by the SBO. Before placing LP-HPC, position the finish machine throughout the proposed placement area to allow the Engineer to verify the reinforcing steel positioning.

(4) Environmental Conditions. Maintain environmental conditions on the entire bridge deck so the evaporation rate is less than 0.2 lb/sq ft/hr. The temperature of the mixed LC-HPC immediately before placement must be a minimum of 55°F and a maximum of 70°F. With approval by the Engineer, the temperature of the LC-HPC may be adjusted 5°F above or below this range. This may require placing the deck at night, in the early morning or on another day. The evaporation rate (as determined in the American Concrete Institute Manual of Concrete Practice 305R, Chapter 2) is a function of air temperature, LC-HPC temperature, wind speed and relative humidity.

The effects of any fogging required by the Engineer will not be considered in the estimation of the evaporation rate (**subsection 3.0c.(5)**).

Just prior to and at least once per hour during placement of the LC-HPC, the Engineer will measure and record the air temperature, LC-HPC temperature, wind speed, and relative humidity on the bridge deck. The Engineer will take the air temperature, wind, and relative humidity measurements approximately 12 inches above the surface of the deck. With this information, the Engineer will determine the evaporation rate using KDOT software or **FIGURE 710-1**.

When the evaporation rate is equal to or above 0.2 $lb/ft^2/hr$, take actions (such as cooling the LC-HPC, installing wind breaks, sun screens etc.) to create and maintain an evaporation rate less than 0.2 $lb/ft^2/hr$ on the entire bridge deck.

(5) Fogging of Deck Placements. Fogging using hand-held equipment may be required by the Engineer during unanticipated delays in the placing, finishing or curing operations. If fogging is required by the Engineer, do not allow water to drip, flow or puddle on the concrete surface during fogging, placement of absorptive material, or at any time before the concrete has achieved final set.

(6) Placement and Equipment. Place LC-HPC by conveyor belt or concrete bucket. Pumping of LC-HPC will be allowed if the Contractor can show proficiency when placing the approved mix during construction of the qualification slab using the same pump as will be used on the job. Placement by pump will also be allowed with prior approval of the Engineer contingent upon successful placement by pump of the approved mix, using the same pump as will be used for the deck placement, at least 15 days prior to placing LC-HPC in the bridge deck. To limit the loss of air, the maximum drop from the end of a conveyor belt or from a concrete bucket is 5 feet and pumps must be fitted with an air cuff/bladder valve. Do not use chutes, troughs or pipes made of aluminum.

Place LC-HPC to avoid segregation of the materials and displacement of the reinforcement. Do not deposit LC-HPC in large quantities at any point in the forms, and then run or work the LC-HPC along the forms.

Fill each part of the form by depositing the LC-HPC as near to the final position as possible.

The Engineer will obtain sample LC-HPC for tests and cylinders at the discharge end of the conveyor, bucket, or if pumped, the piping.

(7) Consolidation.

- Accomplish consolidation of the LC-HPC on all span bridges that require finishing machines by means of a mechanical device on which internal (spud or tube type) concrete vibrators of the same type and size are mounted (**subsection 154.2**).
- Observe special requirements for vibrators in contact with epoxy coated reinforcing steel as specified in **subsection 154.2**.
- Provide stand-by vibrators for emergency use to avoid delays in case of failure.
- Operate the mechanical device so vibrator insertions are made on a maximum spacing of 12 inch centers over the entire deck surface.

- Provide a uniform time per insertion of all vibrators of 3 to 15 seconds, unless otherwise designated by the Engineer.
- Provide positive control of vibrators using a timed light, buzzer, automatic control or other approved method.
- Extract the vibrators from the LC-HPC at a rate to avoid leaving any large voids or holes in the LC-HPC.
- Do not drag the vibrators horizontally through the LC-HPC.
- Use hand held vibrators (**subsection 154.2**) in inaccessible and confined areas such as along bridge rail or curb.
- When required, supplement vibrating by hand spading with suitable tools to provide required consolidation.
- Reconsolidate any voids left by workers.

Continuously place LC-HPC in any floor slab until complete, unless shown otherwise in the Contract Documents.

d. Construction Joints, Expansion Joints and End of Wearing Surface (EWS) Treatment. Locate the construction joints as shown in the Contract Documents. If construction joints are not shown in the Contract Documents, submit proposed locations for approval by the Engineer.

If the work of placing LC-HPC is delayed and the LC-HPC has taken its initial set, stop the placement, saw the nearest construction joint approved by the Engineer, and remove all LC-HPC beyond the construction joint.

Construct keyed joints by embedding water-soaked beveled timbers of a size shown on the Contract Documents, into the soft LC-HPC. Remove the timber when the LC-HPC has set. When resuming work, thoroughly clean the surface of the LC-HPC previously placed, and when required by the Engineer, roughen the key with a steel tool. Before placing LC-HPC against the keyed construction joint, thoroughly wash the surface of the keyed joint with clean water.

e. Finishing. Strike off bridge decks with a vibrating screed or drum-roller screed, either self-propelled or manually operated by winches and approved by the Engineer. Use a self-oscillating screed on the finish machine, and operate or finish from a position either on the skew or transverse to the bridge roadway centerline. See **subsection 3.0c.(3)**. Do not mount tamping devices or fixtures to drum roller screeds; augers are allowed.

Irregular sections may be finished by other methods approved by the Engineer and detailed in the required QCP. See **subsection 3.0c.(1)**.

Finish the surface by a burlap drag, metal pan or both, mounted to the finishing equipment. Use a float or other approved device behind the burlap drag or metal pan, as necessary, to remove any local irregularities. Do not add water to the surface of LC-HPC. Do not use a finishing aid.

Tining of plastic LC-HPC is prohibited. All LC-HPC surfaces must be reasonably true and even, free from stone pockets, excessive depressions or projections beyond the surface.

Finish all top surfaces, such as the top of retaining walls, curbs, abutments and rails, with a wooden float by tamping and floating, flushing the mortar to the surface and provide a uniform surface, free from pits or porous places. Trowel the surface producing a smooth surface, and brush lightly with a damp brush to remove the glazed surface.

f. Curing and Protection.

(1) General. Cure all newly placed LC-HPC immediately after finishing, and continue uninterrupted for a minimum of 14 days. Cure all pedestrian walkway surfaces in the same manner as the bridge deck. Curing compounds are prohibited during the 14 day curing period.

(2) Cover With Wet Burlap. Soak the burlap a minimum of 12 hours prior to placement on the deck. Rewet the burlap if it has dried more one hour before it is applied to the surface of bridge deck. Apply 1 layer of wet burlap within 10 minutes of LC-HPC strike-off from the screed, followed by a second layer of wet burlap within 5 minutes. Do not allow the surface to dry after the strike-off, or at any time during the cure period. In the required QCP, address the rate of LC-HPC placement and finishing methods that will affect the period between strike-off and burlap placement. See **subsection 3.0c.(1)**. During times of delay expected to exceed 10 minutes, cover all concrete that has been placed, but not finished, with wet burlap.

Maintain the wet burlap in a fully wet condition using misting hoses, self-propelled, machine-mounted fogging equipment with effective fogging area spanning the deck width moving continuously across the entire burlap-covered surface, or other approved devices until the LC-HPC has set sufficiently to allow foot traffic. At that time, place soaker hoses on the burlap, and supply running water continuously to maintain continuous saturation of all burlap material to the entire LC-HPC surface. For bridge decks with superelevation, place a minimum of 1 soaker hose along the high edge of the deck to keep the entire deck wet during the curing period.

(3) Waterproof Cover. Place white polyethylene film on top of the soaker hoses, covering the entire LC-HPC surface after soaker hoses have been placed, a maximum of 12 hours after the placement of the LC-HPC. Use as wide of sheets as practicable, and overlap 2 feet on all edges to form a complete waterproof cover of the entire LC-HPC surface. Secure the polyethylene film so that wind will not displace it. Should any portion of the sheets be broken or damaged before expiration of the curing period, immediately repair the broken or damaged portions. Replace sections that have lost their waterproof qualities.

If burlap and/or polyethylene film is temporarily removed for any reason during the curing period, use soaker hoses to keep the entire exposed area continuously wet. Replace saturated burlap and polyethylene film, resuming the specified curing conditions, as soon as possible.

Inspect the LC-HPC surface once every 6 hours for the entirety of the 14 day curing period, so that all areas remain wet for the entire curing period and all curing requirements are satisfied.

(4) Documentation. Provide the Engineer with a daily inspection set that includes:

- documentation that identifies any deficiencies found (including location of deficiency);
- documentation of corrective measures taken;
- a statement of certification that the entire bridge deck is wet and all curing material is in place;
- documentation showing the time and date of all inspections and the inspector's signature.
- documentation of any temporary removal of curing materials including location, date and time, length of time curing was removed, and means taken to keep the exposed area continuously wet.

(5) Cold Weather Curing. When LC-HPC is being placed in cold weather, also adhere to **07-PS0166, latest version**.

When LC-HPC is being placed and the ambient air temperature may be expected to drop below 40ºF during the curing period or when the ambient air temperature is expected to drop more than 25°F below the temperature of the LC-HPC during the first 24 hours after placement, provide suitable measures such as straw, additional burlap, or other suitable blanketing materials, and/or housing and artificial heat to maintain the LC-HPC and girder temperatures between 40ºF and 75ºF as measured on the upper and lower surfaces of the LC-HPC. Enclose the area underneath the deck and heat so that the temperature of the surrounding air is as close as possible to the temperature of LC-HPC and between 40ºF and 75ºF. When artificial heating is used to maintain the LC-HPC and girder temperatures, provide adequate ventilation to limit exposure to carbon dioxide if necessary. Maintain wet burlap and polyethylene cover during the entire 14 day curing period. Heating may be stopped after the first 72 hours if the time of curing is lengthened to account for periods when the ambient air temperature is below 40ºF. For every day the ambient air temperature is below 40ºF, an additional day of curing with a minimum ambient air temperature of 50ºF will be required. After completion of the required curing period, remove the curing and protection so that the temperature of the LC-HPC during the first 24 hours does not fall more than 25°F.

(6) Curing Membrane. At the end of the 14-day curing period remove the wet burlap and polyethylene and within 30 minutes, apply 2 coats of an opaque curing membrane to the LC-HPC. Apply the curing membrane when no free water remains on the surface but while the surface is still wet. Apply each coat of curing membrane according to the manufacturer's instructions with a minimum spreading rate per coat of 1 gallon per 80 square yards of LC-HPC surface. If the LC-HPC is dry or becomes dry, thoroughly wet it with water applied as a fog spray by means of approved equipment. Spray the second coat immediately after and at right angles to the first application.

Protect the curing membrane against marring for a minimum of 7 days. Give any marred or disturbed membrane an additional coating. Should the curing membrane be subjected to continuous injury, the Engineer may limit work on the deck until the 7-day period is complete. Because the purpose of the curing membrane is to allow for slow drying of the bridge deck, extension of the initial curing period beyond 14 days, while permitted, shall not be used to reduce the 7-day period during which the curing membrane is applied and protected.

(7) Construction Loads. Adhere to **TABLE 710-2**.

If the Contractor needs to drive on the bridge before the approach slabs can be placed and cured, construct a temporary bridge from the approach over the EWS capable of supporting the anticipated loads. Do not bend the reinforcing steel which will tie the approach slab to the EWS or damage the LC-HPC at the EWS. The method of bridging must be approved by the Engineer.

TABLE 710-2: CONCRETE LOAD LIMITATIONS ON BRIDGE DECKS

Days after concrete is placed	Element	Allowable Loads
1*	Subdeck, one-course deck or concrete overlay	Foot traffic only.
3*	One-course deck or concrete overlay	Work to place reinforcing steel or forms for the bridge rail or barrier.
7*	Concrete overlays	Legal Loads; Heavy stationary loads with the Engineer's approval.***
10 (15)**	Subdeck, one-course deck or post-tensioned haunched slab bridges**	Light truck traffic (gross vehicle weight less than 5 tons).****
14 (21)**	Subdeck, one-course deck or post-tensioned haunched slab bridges**	Legal Loads; Heavy stationary loads with the Engineer's approval.***Overlays on new decks.
28	Bridge decks	Overloads, only with the State Bridge Engineer's approval.***

*Maintain a 7 day wet cure at all times (14-day wet cure for decks with LC-HPC).
** Conventional haunched slabs.
*** Submit the load information to the appropriate Engineer. Required information: the weight of the material and the footprint of the load, or the axle (or truck) spacing and the width, the size of each tire (or track length and width) and their weight.
****An overlay may be placed using pumps or conveyors until legal loads are allowed on the bridge.

g. Grinding and Grooving. Correct surface variations exceeding 1/8 inch in 10 feet by use of an approved profiling device, or other methods approved by the Engineer after the curing period. Perform grinding on hardened LC-HPC after the 7 day curing membrane period to achieve a plane surface and grooving of the final wearing surface as shown in the Contract Documents.

Use a self-propelled grinding machine with diamond blades mounted on a multi-blade arbor. Avoid using equipment that causes excessive ravels, aggregate fractures or spalls. Use vacuum equipment or other continuous methods to remove grinding slurry and residue.

After any required grinding is complete, give the surface a suitable texture by transverse grooving. Use diamond blades mounted on a self-propelled machine that is designed for texturing pavement. Transverse grooving of the finished surface may be done with equipment that is not self-propelled providing that the Contractor can show proficiency with the equipment. Use equipment that does not cause strain, excessive raveling, aggregate fracture, spalls, disturbance of the transverse or longitudinal joint, or damage to the existing LC-HPC surface. Make the grooving approximately 3/16 inch in width at 3/4 inch centers and the groove depth approximately 1/8 inch. For bridges with drains, terminate the transverse grooving approximately 2 feet in from the gutter line at the base of the curb. Continuously remove all slurry residues resulting from the texturing operation.

h. Post Construction Conference. At the completion of the deck placement, curing, grinding and grooving for a bridge using LC-HPC, a post-construction conference will be held with all parties that participated in the planning and construction present. The Engineer will record the discussion of all problems and successes for the project.

i. Removal of Forms and Falsework. Do not remove forms and falsework without the Engineer's approval. Remove deck forms approximately 2 weeks (a maximum of 4 weeks) after the end of the curing period (removal of burlap), unless approved by the Engineer. The purpose of 4 week maximum is to limit the moisture gradient between the bottom and the top of the deck.

For additional requirements regarding forms and falsework, see **SECTION 708**.

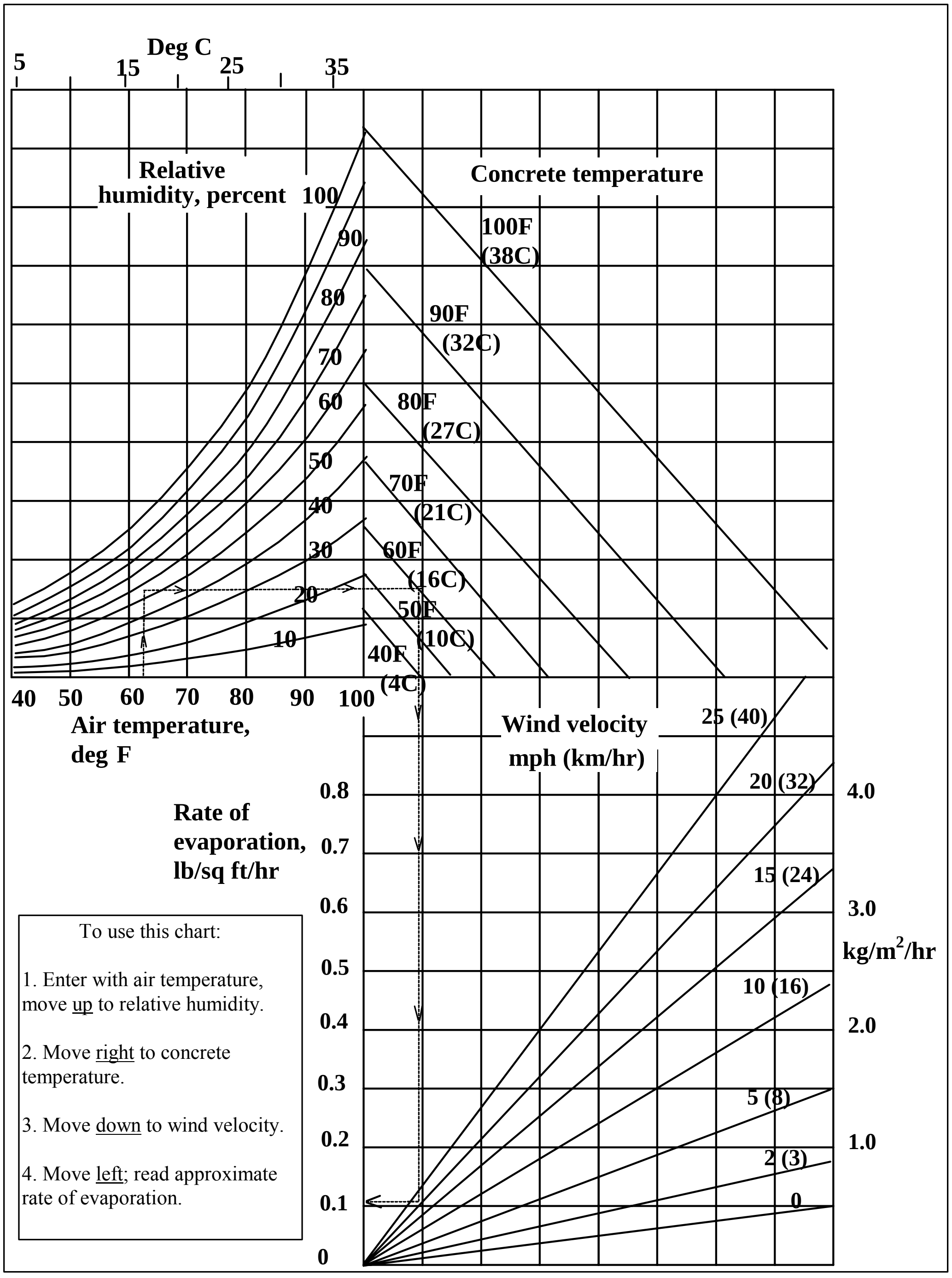
4.0 MEASUREMENT AND PAYMENT

The Engineer will measure the qualification slab and the various grades of (AE) (LC-HPC) concrete placed in the structure by the cubic yard. No deductions are made for reinforcing steel and pile heads extending into the LP-HPC. The Engineer will not separately measure reinforcing steel in the qualification slab.

Payment for the "Qualification Slab" and the various grades of "(AE) (LC-HPC) Concrete" at the contract unit prices is full compensation for the specified work.

07-29-09 LAL
PS0167

FIGURE 710-1: STANDARD PRACTICE FOR CURING CONCRETE



Effect of concrete and air temperatures, relative humidity, and wind velocity on the rate of evaporation of surface moisture from concrete. This chart provides a graphic method of estimating the loss of surface moisture for various weather conditions. To use the chart, follow the four steps outlined above. When the evaporation rate exceeds 0.2 lb/ft^2/hr (1.0 kg/ m^2/hr), measures shall be taken to prevent excessive moisture loss from the surface of unhardened concrete; when the rate is less than 0.2 lb/ft^2/hr (1.0 kg/m^2/hr) such measures may be needed. When excessive moisture loss is not prevented, plastic cracking is likely to occur.

APPENDIX D

BRIDGE DATA

D.1 GENERAL

Appendix D contains data for the LC-HPC and Control bridge decks, including contract and design details, construction dates and methods, site conditions, concrete mix design, average and individual plastic concrete test results, and individual burlap placement times for each placement.

Table D.1 – Low-Cracking High Performance Concrete (LC-HPC) and Control Bridges

County and Serial Number	Bridge Description	LC-HPC Number	Contract Group	Date of Letting	Project Number	Contract Number	Contractor
105-304	EB Parallel Pkwy over I-635	1	1	9/15/2004	K-6371-01	504081011	Clarkson
105-310	34th Street over I-635	2		9/15/2004	K-6371-01		Clarkson
105-311	WB Parallel Pkwy over I-635	Control 1/2		9/15/2004	K-6371-01		Clarkson
56-155	US-50 over BNSF RR	Control 11	2	1/19/2005	K-6829-01	505012031	Cohron
46-338	WB 103rd St over US-69	3	3	8/17/2005	K-8262-01	505091021	Clarkson
46-339	Unit 1: SB US-69 to I-435 Ramp over 103rd St to SB US-69 Ramp	4		8/17/2005	K-8262-01		Clarkson
46-340	Unit 1: SB US-69 to WB I-435 ramp over WB I-435 to Quivera ramp	5		8/17/2005	K-8262-01		Clarkson
46-340	Unit 2: SB US-69 to WB I-435 ramp over WB I-435 to College ramp	6		8/17/2005	K-8262-01		Clarkson
46-337	EB 103rd St over US-69	Control 3		8/17/2005	K-8262-01		Clarkson
46-347	Antioch to WB I-435 & NB US-69 ramp/WB I-435 to NB US-69 ramp	Control 4		8/17/2005	K-8262-01		Clarkson
46-341	Unit 3: SB US-69 to EB I-435 ramp over US-69 and I-435	Control 5		8/17/2005	K-8262-01		Clarkson
46-341	Unit 4: SB US-69 to EB I-435 ramp over US-69 and I-435	Control 6		8/17/2005	K-8262-01		Clarkson
46-334	NB Antioch over I-435	Control 7	4	8/17/2005	K-7451-01	505091011	Clarkson
43-033	Co Rd 150 over US-75	7	5	10/19/2005	K-8260-01	505122031	Capital
54-053	E 1350 Rd over US-69	8†	6	7/19/2006	K-7891-01	506072514	Cohron
54-057	NB US-69 over Marais Des Cygnes River	9		7/19/2006	K-7891-01		United
54-060	E 1800 Rd over US-69	10†		7/19/2006	K-7891-01		Cohron
54-059	K-52 over US-69	Control 8/10†		7/19/2006	K-7891-01		Cohron
54-058	SB US-69 over Marais Des Cygnes River	Control 9		7/19/2006	K-7891-01		United

† Prestressed girders.

Table D.1 (continued) – Low-Cracking High Performance Concrete (LC-HPC) and Control Bridges

County and Serial Number	Bridge Description	LC-HPC Number	Contract Group	Date of Letting	Project Number	Contract Number	Contractor
78-119	EB US-50 over K&O RR	11	7	8/16/2006	K-7409-01	506092515	King
56-057	Unit 2: K-130 over Neosho River	12	8	11/15/2006	K-7445-01	506122051	Cohron
56-057	Unit 1: K-130 over Neosho River	Control 12		11/15/2006	K-7445-01		Cohron
54-066	NB US-69 over BNSF RR	13	9	1/17/2007	K-7892-01	507012444	Beachner
54-067	SB US-69 over BNSF RR	Control 13		1/17/2007	K-7892-01		Beachner
46-363	Metcalf Ave over Indian Creek	14	10	3/26/2007	169-46 N-0314-01	-	Pyramid
56-049	K-52 over US-69	Control Alt†	NA	3/16/2005	K-9440-01	505036071	King

†Monolithic control deck.

Table D.2a – Low-Cracking High Performance Concrete (LC-HPC) and Control Bridge Design Data

LC-HPC Number	Girder Material	Bridge Length (m)	Bridge Length (ft)	Skew (deg)	No. of Spans	Span Lengths (m)	Span Lengths (ft)	Girder End-Condition	Rail Type
1	Steel SMCC	47.3	155.2	5	2	23.7-23.7	77.6-77.6	Integral	Jersey
2	Steel SMCC	53.37	175.1	0	2	26.7-26.7	87.6-87.6	Integral	Corral
Control 1/2	Steel SMCC	47.3	155.2	5	2	23.7-23.7	77.6-77.6	Integral	Jersey
Control 11	Steel SMCC	86.83	284.9	24.3	3	25.4-36.0-25.4	83.3-118.1-83.3	Integral	Jersey
3	Steel SWCC	115.91	380.3	6	4	22.2-35.3-35.3-22.2	72.9-115.8-115.8-72.9	Non-integral	Solid Corral
4	Steel WMCC	115.4	378.6	0	4	25.4-32.0-32.0-25.93	83.3-105.0-105.0-85.1	Integral-Non-integral	Jersey
5	Steel WWCC	169.0	554.5	curved	4	29.38-50.0-50.0-39.91	96.4-164.0-164.0-131.0	Non-integral	Jersey
6	Steel WWCC	181.0	593.8	curved	4	39.79-51.0-51.0-38.91	130.5-167.3-167.3-127.7	Non-integral	Jersey
Control 3	Steel SWCC	115.91	380.3	6	4	22.2-35.3-35.3-22.2	72.9-115.8-115.8-72.9	Non-integral	Solid Corral
Control 4	Steel WWCC	213.8	701.5	0	5	40.8-51.0-51.0-40.0-30.3	133.9-167.3-167.3-131.2-99.4	Non-integral	Jersey
Control 5	Steel WWCC	250.6	822.2	curved	4	45.6-71.0-71.0-63.0	149.6-232.9-232.9-206.7	Non-integral	Jersey
Control 6	Steel WWCC	268.9	882.2	curved	4	64.9-73.0-73.0-58.0	212.8-239.5-239.5-190.3	Non-integral-Integral	Jersey
Control 7	Steel SWCC	58.80	192.9	3.3	2	27.4-31.4	89.9-103.0	Integral	Solid Corral

Table D.2a (continued) – Low-Cracking High Performance Concrete (LC-HPC) and Control Bridge Design Data

LC-HPC Number	Girder Material	Bridge Length (m)	Bridge Length (ft)	Skew (deg)	No. of Spans	Span Lengths (m)	Span Lengths (ft)	Girder End-Condition	Rail Type
7	Steel WMCC	85.0	278.8	0	2	42.5-42.5	139.4-139.4	Integral	Jersey
8	PS† PBMC	92.35	303.0	0	4	18.0-27.8-27.8-18.0	59.1-91.2-91.2-59.1	Integral	Corral
9	Steel WWCC	131.65	431.9	24.4††	3	40.0-50.0-40.0	131.2-164.0-131.2	Non-integral	Corral
10	PS† PBMC	102.07	334.9	21.3	4	22.5-29.8-29.8-19.1	73.8-97.8-97.8-62.3	Integral	Corral
Control 8/10	PS† PBMC	96.85	317.7	0	4	22.0-27.80-27.80-18.50	72.2-91.2-91.2-60.7	Integral	Corral
Control 9	Steel WWCC	131.65	431.9	23.9††	3	40.0-50.0-40.0	131.2-164.0-131.2	Non-integral	Corral
11	Steel WMCC	35.9	117.78	0	3	10.95-14.0-10.95	35.9-45.9-35.9	Integral	Jersey
12	Steel WWCC	126.98	416.5	0	3	43.00-43.45-39.63	141.0-142.5-130.0	Integral	Corral
Control 12	Steel WWCC	126.96	416.5	0	3	39.63-43.45-43.00	130.0-142.5-141.0	Integral	Corral
13	Steel WMCC	90.10	296.6	34.8	3	27.5-35.0-27.5	90.4-114.8-90.4	Integral	Jersey
Control 13	Steel WMCC	90.10	296.6	34.8	3	27.5-35.0-27.5	90.4-114.8-90.4	Integral	Jersey
14	Steel	66.33	217.6	18.0	3	20.5-25.3-20.5	67.3-83.0-67.3	Integral	Corral
Control Alt	Steel SMCC	54.7	179.6	21.5	4	12.1-15.2-15.2-12.1	39.8-50.0-50.0-39.8	Non-integral	Corral

† Prestressed concrete girders.

†† Average skew. Each pier and abutment has a different skew.

Table D.2b – Low-Cracking High Performance Concrete (LC-HPC) and Control Deck Design Data

LC-HPC Number	Deck Width		Deck Thickness		Top Cover		Top Transverse Steel				Bottom Cover		Overlay Thickness	
							Size		Spacing					
	(m)	(ft)	(mm)	(in)	(mm)	(in)	(mm)	(No)	(mm)	(in)	(mm)	(in)	(mm)	(in)
1	22.9	75.1	220	8.7	75	3.0	16	5	150	5.9	30	1.2	NA	NA
2	13.4	44.0	210	8.3	65	2.6	16	5	180	7.1	30	1.2	NA	NA
Control 1/2	20.75	68.07	220	8.7	75	3.0	16	5	150	5.9	30	1.2	40	1.6
Control 11	20.35	66.8	220	8.7	75	3	16	5	180	7.1	30	1.2	40	1.6
3	15.21	49.9	220	8.7	75	3	16	5	160	6.3	30	1.2	NA	NA
4	12.43	40.78	220	8.7	75	3	19	6	250	9.8	30	1.2	NA	NA
5	8.73	28.6	220	8.7	75	3	19	6	180	7.1	30	1.2	NA	NA
6	8.73	28.6	220	8.7	75	3	19	6	180	7.1	30	1.2	NA	NA
Control 3	16.41	53.8	220	8.7	75	3	16	5	160	6.3	30	1.2	40	1.6
Control 4	12.43	40.78	220	8.7	75	3	19	6	250	9.8	30	1.2	40	1.6
Control 5	12.43	40.78	230	9.1	75	3	19	6	180	7.1	30	1.2	40	1.6
Control 6	12.43	40.78	230	9.1	75	3	19	6	180	7.1	30	1.2	40	1.6
Control 7	18.90	62.0	220	8.7	75	3	16	5	160	6.3	30	1.2	40	1.6
7	16.65	54.61	220	8.7	75	3	16 & 19 alternate	5 & 6 alternate	160	6.3	30	1.2	NA	NA
8	11.60	30.1	210	8.3	65	2.6	16	5	170	6.7	35	1.4	NA	NA
9	12.80	42.0	220	8.7	75	3	16	5	180	7.1	35	1.4	NA	NA
10	11.60	30.1	210	8.3	65	2.6	16	5	170	6.7	35	1.4	NA	NA
Control 8/10	12.80	42.0	210	8.3	65	2.6	16	5	170	6.7	30	1.2	NA	NA
Control 9	12.80	42.0	220	8.7	75	3	16	5	180	7.1	30	1.2	40	1.6
11	12.95	42.5	220	8.7	75	3	16	5	175	6.9	30	1.2	NA	NA
12	11.59	38.0	216	8.5	75	3	16	5	152	6	38	1.5	NA	NA
Control 12	11.59	38.0	216	8.5	75	3	16	5	152	6	25	1.0	38	1.5
13	12.95	42.5	220	8.7	75	3	16	5	180	7.1	35	1.4	NA	NA
Control 13	12.95	42.5	220	8.7	75	3	16	5	180	7.1	30	1.2	40	1.6
14	42.67	140.0	216	8.5	75	3	19	6	178	7	25	1	NA	NA
Control Alt	9.75	32.0	216	8.5	64	2.5	19	6	165	6.5	25	1	NA	NA

† Prestressed concrete girders.

Table D.3 – Low-Cracking High Performance Concrete (LC-HPC) Deck Dates of Construction

LC-HPC Number	Date of Letting	Date of Prebid and Preconstruction Conferences	Portion Placed	Date of Placement	Date of Post-Construction Conference
1	9/15/2004	8/31/2004 prebid; 3/8/2005 preconstruction	Qualification Batch	6/23/2005	2/20/2006
			Qualification Slab – attempt 1	7/12/2005	
			Qualification Slab – attempt 2	9/8/2005	
			Deck – placement 1 (south)	10/14/2005	
			Deck – placement 2 (north)	11/2/2005	
2	9/15/2004	8/31/2004 prebid; 3/8/2005 preconstruction	Qualification Batch	6/23/2005	3/13/2007
			Qualification Slab	5/24/2006	
			Deck	9/13/2006	
Control 1/2	9/15/2004	NA	Subdeck (north)	9/30/2005	NA
			Subdeck (south)	10/18/2005	
			SFO (north)	10/10/2005	
			SFO (south)	10/28/2005	
3	8/17/2005	8/2/2005 Prebid	Qualification Batch	6/7/2007	5/28/2008
			Qualification Slab	9/14/2007	
			Deck	11/13/2007	
4	8/17/2005	8/2/2005 Prebid	Qualification Batch	6/7/2007	5/28/2008
			Qualification Slab	9/14/2007	
			Deck – stopped at header	9/29/2007	
			Deck - completed	10/2/2007	
5	8/17/2005	8/2/2005 Prebid; 9/12/2007 preconstruction	Qualification Batch	6/7/2007	5/28/2008

Table D.3 (continued) – Low-Cracking High Performance Concrete (LC-HPC) Deck Dates of Construction

LC-HPC Number	Date of Letting	Date of Prebid and Preconstruction Conferences	Portion Placed	Date of Placement	Date of Post-Construction Conference
5 (cont.)			Qualification Slab	9/14/2007	
			Deck	11/14/2007	
6	8/17/2005	8/2/2005 Prebid	Qualification Batch	6/7/2007	5/28/2008
			Qualification Slab	9/14/2007	
			Deck	11/3/2007	
Control 3	8/17/2005	8/2/2005 Prebid	Subdeck	7/6/2007	NA
			SFO	7/17/2007	
Control 4	8/17/2005	8/2/2005 Prebid	Subdeck	10/20/2007	NA
			SFO	11/16/2007	
Control 5	8/17/2008	8/2/2005 Prebid	Subdeck – placement 1 (seq. 1 & 2)	11/8/2008	NA
			Subdeck – placement 2 (seq. 3, 5, & 6)	11/13/2008	
			Subdeck – placement 3 (seq. 4 & 7)	11/17/2008	
			SFO – placement 1 (west half)	11/22/2008	
			SFO – placement 2 (east half)	11/25/2008	
Control 6	8/17/2005	8/2/2005 Prebid	Subdeck – placement 1 (seq. 1 & 2)	9/16/2008	NA
			Subdeck – placement 2 (seq. 3)	9/18/2008	
			Subdeck – placement 3 (seq. 5 & 6)	9/23/2008	
			Subdeck – placement 4 (seq. 4)	9/26/2008	
			Subdeck – placement 5 (seq. 7)	9/30/2008	

Table D.3 (continued) – Low-Cracking High Performance Concrete (LC-HPC) Deck Dates of Construction

LC-HPC Number	Date of Letting	Date of Prebid and Preconstruction Conferences	Portion Placed	Date of Placement	Date of Post-Construction Conference
Control 6 (cont.)			SFO – placement 1	10/16/2008	
			SFO – placement 2	10/20/2008	
Control 7	8/17/2005	NA	Subdeck – placement 1 (W 2/3)	3/15/2006	NA
			Subdeck – placement 2 (E 1/3)	8/16/2006	
			SFO – placement 1 (W 2/3)	3/29/2006	
			SFO – placement 2 (E 1/3)	9/15/2006	
7	10/19/2005	10/10/2005 Prebid	Qualification Batch	5/31/2006	10/17/2006
			Qualification Slab	6/8/2006	
			Deck	6/24/2006	
8	7/19/2006	7/6/2006 Prebid	Qualification Batch	4/11/2007	10/22/2007 teleconference
			Qualification Slab	9/26/2007	
			Deck	10/3/2007	
9	7/19/2006	7/6/2006 Prebid	Qualification Batch	3/25/09	6/3/2009
			Qualification slab – attempt 1	3/23/2009	
			Qualification Slab – attempt 2	3/25/2009	
			Qualification Slab – attempt 3 completed	4/1/2009	4/1/2009 meeting after qual slab to discuss pour
			Deck	4/15/2009	
10	7/19/2006	7/6/2006 Prebid	Qualification Batch	4/11/2007	5/29/2007
			Qualification Slab	4/26/2007	
			Deck	5/17/2007	
Control 8 /10	7/19/2006	7/6/2006 Prebid	Deck	4/16/2007	NA
Control 9	7/19/2006	7/6/2006 Prebid	Subdeck	11/3/2007	NA
			SFO – placement 1 (east)	5/21/2008	

Table D.3 (continued) – Low-Cracking High Performance Concrete (LC-HPC) Deck Dates of Construction

LC-HPC Number	Date of Letting	Date of Prebid and Preconstruction Conferences	Portion Placed	Date of Placement	Date of Post-Construction Conference
Control 9 (cont.)			SFO – placement 2 (west)	5/29/2008	
11	8/16/2006	7/28/2006 Prebid	Qualification Batch #1	5/23/2007	9/28/2007
			Qualification Slab	5/25/2007	
			Qualification Batch #2	6/7/2007	
			Deck	6/9/2007	
Control 11	1/19/2005	NA	Subdeck – placement 1 (North 1/2)	2/3/2006	NA
			Subdeck – placement 2 (South 1/2)	2/14/2006	
			SFO	3/28/2006	
12	11/15/2006	10/30/2006 Prebid	Qualification Batch – phase 1	3/25/2008	-
			Qualification Slab	3/28/2008	
			Deck – phase 1 (east)	4/4/2008	
			Qualification Batch – phase 2	3/12/2009	
			Deck – phase 2 (west)	3/18/2009	
Control 12	11/15/2006	10/30/2006 Prebid	Subdeck – phase 1 (east)	3/11/2008	NA
			SFO – phase 1 (east)	4/1/2008	
			Subdeck – phase 2 (west)	3/13/2009	
			SFO – phase 2 (west)	4/14/2009	
13	1/17/2007	1/8/2007 Prebid	Qualification Batch	4/15/2008	6/3/2009
			Qualification Slab	4/16/2008	
			Deck	4/29/2008	

Table D.3 (continued) – Low-Cracking High Performance Concrete (LC-HPC) Deck Dates of Construction

LC-HPC Number	Date of Letting	Date of Prebid and Preconstruction Conferences	Portion Placed	Date of Placement	Date of Post-Construction Conference
Control 13	1/17/2007	NA	Subdeck	7/11/2008	NA
			SFO	7/25/2008	
14	3/26/2007 check	Prebid 3/19/2007; Preconstruction 9/26/2007	Qualification Batch	None. Same concrete as Contract Group 3 (Table D.1)	3/4/2008
			Qualification Slab	11/13/2007	
			Deck placement 1 - Phase 1 attempt 1 (Center)	11/19/2007	
			Deck placement 1 attempt 2 - Phase 1 (Center)	12/19/2007	
			Deck placement 2 – Phase 2 (West)	5/2/2008	
			Deck placement 3 – Phase 2 (East)	5/21/2008	
Control Alt	3/16/2005	NA	Deck	6/2/2005	NA

Table D.4a – Low-Cracking High Performance Concrete (LC-HPC) Construction Methods

LC-HPC Number	Portion Placed	Date of Placement	Avg. Haul Time (min.)	Method of Concrete Temperature Control	Placement Method	Fogging*
1	Qualification Slab – attempt 1	7/12/2005	-	Chilled Water - insufficient	NA	NA
	Qualification Slab – attempt 2	9/8/2005	NR	Chilled water - sufficient	Pump	Machine and hand-held. 10 nozzles w/ flexible tubing. Deposited water on deck, turned off.
	Deck – placement 1 (south)	10/14/2005	51	None	Pump	2 nozzles mounted 0.9 m (3 ft) above screed, pointed down. Water on deck worked into surface
	Deck – placement 2 (north)	11/2/2005	-	None	Pump	2 nozzles mounted on screed 30 cm (12 in.) above deck. Sprayed water on deck, used as finishing aid.
2	Qualification Slab	5/24/2006	NR	Chilled water, ice	Pump	Not used
	Deck	9/13/2006	43	Chilled water, ice	Pump	Not used
Control 1/2	Subdeck (north)	9/30/2005	-	-	-	-
	Subdeck (south)	10/18/2005	-	-	-	-
	SFO (north)	10/10/2005	-	-	-	-
	SFO (south)	10/28/2005	-	-	-	-
3	Qualification Slab	9/14/2007	Same as LC-HPC-4	Same as LC-HPC-4	Same as LC-HPC-4	Same as LC-HPC-4
	Deck	11/13/2007		None	Pump	Not used
4	Qualification Slab	9/14/2007	-	Ice and chilled water	Pump	Fogging was pre-qualified. Nozzles pointed down and sprayed concrete. Corrected then turned off.
	Deck – stopped at header	9/29/2007	49	Ice and chilled water	Pump	Used extensively during delays

Table D.4a (continued) – Low-Cracking High Performance Concrete (LC-HPC) Construction Methods

LC-HPC Number	Portion Placed	Date of Placement	Avg. Haul Time (min.)	Method of Concrete Temperature Control	Placement Method	Fogging*
4 Continued	Deck - completed	10/2/2007	60	Ice and chilled water	Pump	Not used, even when requested during delay at end of pour
5	Qualification Slab	9/14/2007	Same as LC-HPC-4	Same as LC-HPC-4	Same as LC-HPC-4	Same as LC-HPC-4
	Deck	11/14/2007	58	None. Wrapped and heated girders	Pump	Not used
6	Qualification Slab	9/14/2007	Same as LC-HPC-4	Same as LC-HPC-4	Same as LC-HPC-4	Same as LC-HPC-4
	Deck	11/3/2007	62	None. Wrapped and heated girders	Pump	Not used
Control 3	Subdeck	7/6/2007	-	-	-	-
	SFO	7/17/2007	-	-	-	-
Control 4	Subdeck	10/20/2007	-	-	-	-
	SFO	11/16/2007	80	-	-	-
Control 5	Subdeck – placement 1 (seq. 1 & 2)	11/8/2008	-	-	-	-
	Subdeck – placement 2 (seq. 3, 5, & 6)	11/13/2008	-	-	-	-
	Subdeck – placement 3 (seq. 4 & 7)	11/17/2008	-	-	-	-
	SFO – placement 1 (west half)	11/22/2008	-	-	-	-
	SFO – placement 2 (east half)	11/25/2008	-	-	-	-
Control 6	Subdeck – placement 1 (seq. 1 & 2)	9/16/2008	-	-	-	-

Table D.4a (continued) – Low-Cracking High Performance Concrete (LC-HPC) Construction Methods

LC-HPC Number	Portion Placed	Date of Placement	Avg. Haul Time (min.)	Method of Concrete Temperature Control	Placement Method	Fogging*
Control 6 Continued	Subdeck – placement 2 (seq. 3)	9/18/2008	-	-	-	-
	Subdeck – placement 3 (seq. 5 & 6)	9/23/2008	-	-	-	-
	Subdeck – placement 4 (seq. 4)	9/26/2008	-	-	-	-
	Subdeck – placement 5 (seq. 7)	9/30/2008	-	-	-	-
	SFO – placement 1	10/16/2008	-	-	-	-
	SFO – placement 2	10/20/2008	-	-	-	-
Control 7	Subdeck – placement 1	3/15/2006	-	-	-	-
	Subdeck – placement 2	8/16/2006	-	-	-	-
	SFO – placement 1	3/29/2006	73	-	-	-
	SFO – placement 2	9/15/2006	-	-	-	-
7	Qualification Batch	5/31/2006	35	Ice	NA	NA
	Qualification Slab	6/8/2006	-	Ice	Pump	Dripped on slab. Turned off.
	Deck	6/24/2006	45	Ice & Chilled Water	Pump	PVC piping. Dripped on slab. Turned off.
8	Qualification Slab	9/26/2007	-	-	Pump	Solid pipe with 10 spray nozzles pointed up. 400 psi. No 6 nozzles. Too much water.
	Deck	10/3/2007	25	Ice	Pump	Solid pipe with 10 spray nozzles pointed up. 1000 psi. No. 4 nozzles. Good fog. Not used most of deck.
9	Qualification Slab – attempt 1	3/23/09	NA	None	Pump – failed	NA
	Qualification Slab – attempt 2	3/25/09	NA	None	Pump - failed	NA

Table D.4a (continued) – Low-Cracking High Performance Concrete (LC-HPC) Construction Methods

LC-HPC Number	Portion Placed	Date of Placement	Avg. Haul Time (min.)	Method of Concrete Temperature Control	Placement Method	Fogging*
9 Continued	Qualification Slab – attempt 3 completed	4/1/2009	38	None	Conveyor	Hand-held, spray test one time
	Deck	4/15/2009	34	None	Conveyor	Not used. Concrete covered with wet burlap during delay.
10	Qualification Slab	4/26/2007	-	-	Pump	Flexible piping, dripped water on deck. Turned off.
	Deck	5/17/2007	47	Ice	Pump	Flexible piping leaked, turned off. Hand-held fogging during delays and as finishing aid.
Control 8/10	Deck	4/16/2007	31	None	Pump	NA
Control 9	Subdeck	11/3/2007	36	NA	Pump	NA
	SFO – placement 1 (east)	5/21/2008	41	None	NA	NA
	SFO – placement 2 (west)	5/29/2008	49	None	NA	NA
11	Qualification Slab	5/25/2007	-	-	Pump	Good fogging no leaking
	Deck	6/9/2007	34	Ice	Conveyor	Good fogging, no leaking, 1st abutment placed out of truck
Control 11	Subdeck – placement 1 (North 1/2)	2/3/2006	29	None	NA	NA
	Subdeck – placement 2 (South 1/2)	2/14/2006	24	None	NA	NA
	SFO	3/28/2006	34	None	NA	NA
12	Qualification Slab	3/28/2008	45	-	Bucket	Solid pipe w/ 5 spray nozzles. Not used.
	Deck – phase 1 (east)	4/4/2008	56	-	Bucket	Not used
	Deck – phase 2 (west)	3/18/2009	61	Heated water	Bucket	Not used
Control 12	Subdeck – phase 1 (east)	3/11/2008	55	Unknown	NA	NA
	SFO – phase 1 (east)	4/1/2008	90	Unknown	NA	NA
	Subdeck – phase 2 (west)	3/13/2009	70	None	NA	NA
	SFO – phase 2 (west)	4/14/2009	62	Unknown	NA	NA

Table D.4a (continued) – Low-Cracking High Performance Concrete (LC-HPC) Construction Methods

LC-HPC Number	Portion Placed	Date of Placement	Avg. Haul Time (min.)	Method of Concrete Temperature Control	Placement Method	Fogging*
13	Qualification Slab	4/16/2008	-	None	Pump	No fogging equipment
	Deck	4/29/2008	18	None	Pump	Solid pipe with nozzles. Dripped when turned off.
Control 13	Subdeck	7/11/2008	21	None	-	-
	SFO	7/25/2008	14	None	-	-
14	Qualification Slab	11/13/2007	-	-	Pump	Fogging equipment did not drip
	Deck placement 1 - Phase 1 attempt 1 (Center)	11/19/2007	Concrete removed	-	Pump	Fogging equipment did not drip
	Deck placement 1 attempt 2 - Phase 1 (Center)	12/19/2007	-	None	Conveyor	Fogging equipment dripped
	Deck placement 2 - Phase 2 (West)	5/2/2008	-	Ice and chilled water	Conveyor	Hand fogging used during delay
	Deck placement 3 - Phase 2 (East)	5/21/2008	-	Ice and chilled water	Conveyor	Not used
Control Alt	Deck	6/2/2005	51	None	NA	NA

Based on experience, only fogging with hand-held equipment is now recommended and then only when there is a delay in the concrete finishing operation.

† Prestressed concrete girders.

NR = Not recorded.

Table D.4b – Low-Cracking High Performance Concrete (LC-HPC) Construction Methods

LC-HPC Number	Portion Placed	Date of Placement	Finishing Method	Time to Burlap Placement			Time to Form Removal†
				Avg (min.)	Min (min.)	Max (min.)	(days)
1	Qualification Slab – attempt 2	9/8/2005	Single-drum roller screed / bullfloat	21	4	38	NA
	Deck – placement 1 (south)	10/14/2005	Single-drum roller screed / bullfloat	16	11	29	5, 6, 10, 11, 12
	Deck – placement 2 (north)	11/2/2005	Single-drum roller screed / bullfloat	11	7	17	29, 30, 49, 82, 83
2	Qualification Slab	5/24/2006	Single-drum roller screed / bullfloat	-	-	-	NA
	Deck	9/13/2006	Single-drum roller screed / bullfloat	16	10	28	17, 19, 20, 50, 51, 52
Control 1/2	Subdeck (north)	9/30/2005	NA	NA	NA	NA	NA
	Subdeck (south)	10/18/2005	NA	NA	NA	NA	NA
	SFO (north)	10/10/2005	NA	NA	NA	NA	NA
	SFO (south)	10/28/2005	NA	NA	NA	NA	NA
3	Qualification Slab	9/14/2007	Same as LC-HPC-4	Same as LC-HPC-4			NA
	Deck	11/13/2007	Single-drum roller screed / bullfloat	15	9	25	13
4	Qualification Slab	9/14/2007	Single-drum roller screed / bullfloat	23	11	36	NA
	Deck – stopped at header	9/29/2007	Single-drum roller screed / bullfloat / wood mop	9	7	13	NA
	Deck - completed	10/2/2007	Single-drum roller screed / bullfloat	16	7	43	24, 27
5	Qualification Slab	9/14/2007	Same as LC-HPC-4	Same as LC-HPC-4			NA
	Deck	11/14/2007	Single-drum roller screed / bullfloat	12	5	22	-
6	Qualification Slab	9/14/2007	Same as LC-HPC-4	Same as LC-HPC-4			NA
	Deck	11/3/2007	Single-drum roller screed / bullfloat	7	2	20	26
Control 3	Subdeck	7/6/2007	NA	NA	NA	NA	NA
	SFO	7/17/2007	NA	NA	NA	NA	NA
Control 4	Subdeck	10/20/2007	NA	NA	NA	NA	13

Table D.4b (continued) – Low-Cracking High Performance Concrete (LC-HPC) Construction Methods

LC-HPC Number	Portion Placed	Date of Placement	Finishing Method	Time to Burlap Placement			Time to Form Removal†
				Avg (min.)	Min (min.)	Max (min.)	(days)
Control 4 Continued	SFO	11/16/2007	NA	NA	NA	NA	NA
Control 5	Subdeck – placement 1 (seq. 1 & 2)	11/8/2008	NA	NA	NA	NA	NA
	Subdeck – placement 2 (seq. 3, 5, & 6)	11/13/2008	NA	NA	NA	NA	NA
	Subdeck – placement 3 (seq. 4 & 7)	11/17/2008	NA	NA	NA	NA	NA
	SFO – placement 1 (west half)	11/22/2008	NA	NA	NA	NA	NA
	SFO – placement 2 (east half)	11/25/2008	NA	NA	NA	NA	NA
Control 6	Subdeck – placement 1 (seq. 1 & 2)	9/16/2008	NA	NA	NA	NA	NA
	Subdeck – placement 2 (seq. 3)	9/18/2008	NA	NA	NA	NA	NA
	Subdeck – placement 3 (seq. 5 & 6)	9/23/2008	NA	NA	NA	NA	NA
	Subdeck – placement 4 (seq. 4)	9/26/2008	NA	NA	NA	NA	NA
	Subdeck – placement 5 (seq. 7)	9/30/2008	NA	NA	NA	NA	NA
	SFO – placement 1	10/16/2008	NA	NA	NA	NA	NA
	SFO – placement 2	10/20/2008	NA	NA	NA	NA	NA
Control 7	Subdeck – placement 1	3/15/2006	NA	NA	NA	NA	NA
	Subdeck – placement 2	8/16/2006	NA	NA	NA	NA	NA
	SFO – placement 1	3/29/2006	NA	NA	NA	NA	NA

Table D.4b (continued) – Low-Cracking High Performance Concrete (LC-HPC) Construction Methods

LC-HPC Number	Portion Placed	Date of Placement	Finishing Method	Time to Burlap Placement			Time to Form Removal†
				Avg (min.)	Min (min.)	Max (min.)	(days)
Control 7 Continued	SFO – placement 2	9/15/2006	NA	NA	NA	NA	NA
7	Qualification Slab	6/8/2006	Double-drum roller screed with one roller removed/pan drag	>10	>10	>10	NA
	Deck	6/24/2006	Double-drum roller screed with one roller removed/pan drag/burlap drag/bullfloat	38	11	90	17–approx. 77
8	Qualification Slab	9/26/2007	Single-drum roller screed/pan drag/bullfloat	12	7	16	NA
	Deck	10/3/2007	Single-drum roller screed/pan drag	12	4	27	16, 27-29, 47
9	Qualification Slab – attempt 1	3/23/09	NA	NA	NA	NA	NA
	Qualification Slab – attempt 2	3/25/09	NA	NA	NA	NA	NA
	Qualification Slab – attempt 3 completed	4/1/2009	Double-drum roller screed with one roller removed / 2 pan drags	9.5	6	12	NA
	Deck	4/15/2009	Double-drum roller screed with one roller removed / 2 pan drags	10	3	18	27 to 42
10	Qualification Slab	4/26/2007	Single-drum roller screed/pan drag/bullfloat	7	-	8	NA
	Deck	5/17/2007	Single-drum roller screed / pan drag	17	6	41	20, 25, 27
Control 8/10	Deck	4/16/2007	NA	NA	NA	NA	34 to 53
Control 9	Subdeck	11/3/2007	NA	NA	NA	NA	151 to 169
	SFO – placement 1 (east)	5/21/2008	NA	NA	NA	NA	NA
	SFO – placement 2 (west)	5/29/2008	NA	NA	NA	NA	NA
11	Qualification Slab	5/25/2007	Single-drum roller screed/ bullfloating	32	14	49	NA
	Deck	6/9/2007	Single-drum roller screed/ pan drag	14	4	19	18
Control 11	Subdeck – placement 1 (North 1/2)	2/3/2006	NA	NA	NA	NA	12, 13, (17)

Table D.4b (continued) – Low-Cracking High Performance Concrete (LC-HPC) Construction Methods

LC-HPC Number	Portion Placed	Date of Placement	Finishing Method	Time to Burlap Placement			Time to Form Removal†
				Avg (min.)	Min (min.)	Max (min.)	(days)
Control 11 Continued	Subdeck – placement 2 (South 1/2)	2/14/2006	NA	NA	NA	NA	(6), 13
	SFO	3/28/2006	NA	NA	NA	NA	NA
12	Qualification Slab	3/28/2008	Single-drum roller screed/fabric drag	5.3	3	10	NA
	Deck – phase 1 (east)	4/4/2008	Single-drum roller screed/pan drag	7	4	12	45-49
	Deck – phase 2 (west)	3/18/2009	Single-drum roller screed/pan drag	6.3	1	24	56, 57, 64, 65, 66
Control 12	Subdeck – phase 1 (east)	3/11/2008	NA	NA	NA	NA	69 - 73
	SFO – phase 1 (east)	4/1/2008	NA	NA	NA	NA	NA
	Subdeck – phase 2 (west)	3/13/2009	NA	NA	NA	NA	11, 18, 19, 20, 25, 28
	SFO – phase 2 (west)	4/14/2009	NA	NA	NA	NA	NA
13	Qualification Slab	4/16/2008	Double-drum roller screed /pan drag/ /bullfloat	14	6	25	NA
	Deck	4/29/2008	Double-drum roller screed / pan drag / bullfloating	12	2	24	72 to 122
Control 13	Subdeck	7/11/2008	NA	NA	NA	NA	NA
	SFO	7/25/2008	NA	NA	NA	NA	NA
14	Qualification Slab	11/13/2007	Double-drum roller screed with one roller removed/pan drag/bullfloat	18	13	25	NA
	Deck placement 1 - Phase 1 attempt 1 (Center)	11/19/2007	Double-drum roller screed with one roller removed/pan drag/bullfloat (concrete removed from deck)	NA	NA	NA	NA
	Deck placement 1 attempt 2 - Phase 1 (Center)	12/19/2007	Double-drum roller screed with one roller removed /pan drag/bullfloat	28	20	40	NA

Table D.4b (continued) – Low-Cracking High Performance Concrete (LC-HPC) Construction Methods

LC-HPC Number	**Portion Placed**	**Date of Placement**	**Finishing Method**	**Time to Burlap Placement**			**Time to Form Removal**†
				Avg (min.)	Min (min.)	Max (min.)	(days)
14 Continued	Deck placement 2 - Phase 2 (West)	5/2/2008	Double-drum roller screed /pan drag/bullfloat/large burlap drag attached to first work bridge	21	12	74	-
	Deck placement 3 - Phase 2 (East)	5/21/2008	Double-drum roller screed/pan drag/large burlap drag attached to first work bridge	15	9	21	-
Control Alt	Deck	6/2/2005	NA	NA	NA	NA	NA

† Time from last concrete placement to form removal in days.

Table D.5a – Field Information and Site Conditions for LC-HPC and Control Decks

LC-HPC Number	Portion Placed	Date of Placement	Wind Speed Low (kmph)	Wind Speed Low (mph)	Wind Speed High (kmph)	Wind Speed High (mph)	% Relative Humidity Low	% Relative Humidity High	Air Temp During Placement Low (°C)	Air Temp During Placement Low (°F)	Air Temp During Placement High (°C)	Air Temp During Placement High (°F)
1	Qualification Slab – attempt 2	9/8/2005	-	-	-	-	-	-	-	-	-	-
	Deck – placement 1 (south)	10/14/2005	2.5	1.5	3.3	2	72	74	11	52	15	59
	Deck – placement 2 (north)	11/2/2005	6.7	4	13.4	8	52	68	11	52	22	72
2	Qualification Slab	5/24/2006	-	-	-	-	-	-	-	-	-	-
	Deck	9/13/2006	1	0.6	1.5	0.9	67	87	13	56	21	70
Control 1/2	Subdeck (north)	9/30/2005	3.3	2	6.7	4	NR	NR	13	55	15	59
	Subdeck (south)	10/18/2005	NR	NR	NR	NR	NR	NR	24	75	24	75
	SFO (north)	10/10/2005	1.7	1	4.2	2.5	30	-	8	46	9	48
	SFO (south)	10/28/2005	4.2	2.5	5	3	30	73	12	54	17	63
3	Qualification Slab	9/14/2007	Same as LC-HPC-4									
	Deck	11/13/2007	0	0	1.7	1	51	72	6	43	12	54
4	Qualification Slab	9/14/2007	1.7	1	3.3	2	46	53	16	61	16	61
	Deck – stopped at header	9/29/2007	1.7	1	3.3	2	59	69	19	66	21	69
	Deck - completed	10/2/2007	1.7	1	1.7	1	69	72	19	66	19	67
5	Qualification Slab	9/14/2007	Same as LC-HPC-4									
	Deck	11/14/2007	1.7	1	5	3	38	64	12	54	13	56
6	Qualification Slab	9/14/2007	Same as LC-HPC-4									
	Deck	11/3/2007	1.7	1	3.3	2	46	73	2	36	13	55
Control 3	Subdeck	7/6/2007	0.6	0.4†	-	-	73†	-	23	73†	-	-
	SFO	7/17/2007	1.0	0.6†	-	-	68†	-	26	78†	-	-
Control 4	Subdeck	10/20/2007	3.4	2.1†	-	-	50†	-	20	68†	-	-
	SFO	11/16/2007	NR	NR	-	-	NR	-	NR	NR	-	-
Control 5	Subdeck – placement 1 (seq. 1 & 2)	11/8/2008	5.6	3.5†	-	-	60†	-	3	38†	-	-

Table D.5a (continued) – Field Information and Site Conditions for LC-HPC and Control Decks

LC-HPC Number	Portion Placed	Date of Placement	Wind Speed Low (kmph)	Wind Speed Low (mph)	Wind Speed High (kmph)	Wind Speed High (mph)	% Relative Humidity Low	% Relative Humidity High	Air Temp During Placement Low (°C)	Air Temp During Placement Low (°F)	Air Temp During Placement High (°C)	Air Temp During Placement High (°F)
Control 5 Continued	Subdeck – placement 2 (seq. 3, 5, & 6)	11/13/2008	8.6	5.4†	-	-	63†	-	12	54†	-	-
	Subdeck – placement 3 (seq. 4 & 7)	11/17/2008	7.2	4.5†	-	-	59†	-	7	44†	-	-
	SFO – placement 1 (west half)	11/22/2008	8.6	5.4†	-	-	49†	-	4	40†	-	-
	SFO – placement 2 (east half)	11/25/2008	5.1	3.2†	-	-	52†	-	7	44†	-	-
Control 6	Subdeck – placement 1 (seq. 1 & 2)	9/16/2008	1.1	0.7†	-	-	76†	-	14	57†	-	-
	Subdeck – placement 2 (seq. 3)	9/18/2008	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
	Subdeck – placement 3 (seq. 5 & 6)	9/23/2008	3.2	2.0†	-	-	71†	-	19	67†	-	-
	Subdeck – placement 4 (seq. 4)	9/26/2008	3.7	2.3†	-	-	58†	-	28	83†	-	-
	Subdeck – placement 5 (seq. 7)	9/30/2008	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
	SFO – placement 1	10/16/2008	2.9	1.8†	-	-	59†	-	11	51†	-	-
	SFO – placement 2	10/20/2008	3.7	2.3†	-	-	72†	-	16	61†	-	-
Control 7	Subdeck – placement 1	3/15/2006	4.0	2.5†	-	-	40†	-	11	52†	-	-
	Subdeck – placement 2	8/16/2006	3.7	2.3†	-	-	59†	-	23	74†	-	-
	SFO – placement 1	3/29/2006	NR	NR	-	-	NR	-	NR	NR	-	-
	SFO – placement 2	9/15/2006	6.4	4.0†	-	-	71†	-	18	64†	-	-
7	Qualification Slab	6/8/2006	-	-	-	-	-	-	-	-	-	-
	Deck	6/24/2006	1.3	0.8	5.2	3.1	72	81	21	70	22	71
8	Qualification Slab	9/26/2007	-	-	-	-	-	-	-	-	-	-
	Deck	10/3/2007	-	-	-	-	-	-	-	-	-	-

Table D.5a (continued) – Field Information and Site Conditions for LC-HPC and Control Decks

LC-HPC Number	Portion Placed	Date of Placement	Wind Speed Low (kmph)	Wind Speed Low (mph)	Wind Speed High (kmph)	Wind Speed High (mph)	% Relative Humidity Low	% Relative Humidity High	Air Temp During Placement Low (°C)	Air Temp During Placement Low (°F)	Air Temp During Placement High (°C)	Air Temp During Placement High (°F)
9	Qualification Slab – attempt 3 completed	4/1/2009	3.2	2.0	3.5	2.2	30	38	13.9	57	16.1	61
	Deck	4/15/2009	0	0	4.6	7.3	35	51	13	56	22	72
10	Qualification Slab	4/26/2007	-	-	-	-	-	-	-	-	-	-
	Deck	5/17/2007	-	-	-	-	-	-	-	-	-	-
Control 8/10	Deck	4/16/2007	-	-	-	-	-	-	19	67	23	73
Control 9	Subdeck	11/3/2007	0	0	13	8	28	78	4	40	14	57
	SFO – placement 1 (east)	5/21/2008	0	0	10	6	52	70	11	52	21	70
	SFO – placement 2 (west)	5/29/2008	10	6	26	16	78	90	16	61	21	70
11	Qualification Slab	5/25/2007	1.9	1.2	5.6	3.5	52	63	21.7	71	23.3	74
	Deck	6/9/2007	1.6	1.0	19.0	11.9	48	66	14	57	22	72
Control 11	Subdeck – placement 1 (North 1/2)	2/3/2006	13[††]	8[††]	30[††]	18[††]	NR	NR	NR	NR	NR	NR
	Subdeck – placement 2 (South 1/2)	2/14/2006	8[††]	5[††]	37[††]	22[††]	NR	NR	NR	NR	NR	NR
	SFO	3/28/2006	0[††]	0[††]	22[††]	13[††]	NR	NR	NR	NR	NR	NR
12	Qualification Slab	3/28/2008	-	-	19	12[††]	48[††]	93[††]	3	38	4	39
	Deck – phase 1 (east)	4/4/2008	0.8	0.5	4	2.5	47	77	7	44	17	63
	Deck – phase 2 (west)	3/18/2009	8.5	5.3	25.8	16.0	-	75.6	11.5	52.7	17.2	63
Control 12	Subdeck – phase 1 (east)	3/11/2008	"light wind"		14[††]	9[††]	26[††]	78[††]	2	36	21	70
	SFO – phase 1 (east)	4/1/2008	"light wind"		24[††]	15[††]	38[††]	82[††]	9	49	11	52
	Subdeck – phase 2 (west)	3/13/2009	1.6	1	8	5	44	56	4	38.5	12	54
	SFO – phase 2 (west)	4/14/2009	"light wind"		10[††]	6[††]	37[††]	93[††]	-	-	-	-
13	Qualification Slab	4/16/2008	-	-	-	-	-	-	-	-	-	-
	Deck	4/29/2008	-	-	-	-	-	-	17	63	22	72
Control 13	Subdeck	7/11/2008	-	-	-	-	-	-	23	73	30	86
	SFO	7/25/2008	-	-	-	-	-	-	29	84	29	85
14	Qualification Slab	11/13/2007	-	-	-	-	-	-	-	-	-	-

Table D.5a (continued) – Field Information and Site Conditions for LC-HPC and Control Decks

LC-HPC Number	Portion Placed	Date of Placement	Wind Speed Low (kmph)	Wind Speed Low (mph)	Wind Speed High (kmph)	Wind Speed High (mph)	% Relative Humidity Low	% Relative Humidity High	Air Temp During Placement Low (°C)	Air Temp During Placement Low (°F)	Air Temp During Placement High (°C)	Air Temp During Placement High (°F)
14 Continued	Deck placement 1 - Phase 1 attempt 1 (Center)	11/19/2007	-	-	-	-	-	-	-	-	-	-
	Deck placement 1 attempt 2 - Phase 1 (Center)	12/19/2007	1.2	0.7	4.2	2.5	38	70	3	37	14	57
	Deck placement 2 - Phase 2 (West)	5/2/2008	8.3	5	-	-	-	78	14	58	-	-
	Deck placement 3 - Phase 2 (East)	5/21/2008	-	-	-	-	-	-	-	-	-	-
Control Alt	Deck	6/2/2005	-	-	-	-	-	-	-	-	-	-

† Average value, provided by KDOT

†† Weather station report

NR = Not recorded

Table D.5b – Field Information and Site Conditions for LC-HPC and Control Decks

LC-HPC Number	Portion Placed	Date of Placement	Evaporation Rate During Placement Low ($kg/m^2/hr$)	Evaporation Rate During Placement Low ($lb/ft^2/hr$)	Evaporation Rate During Placement High ($kg/m^2/hr$)	Evaporation Rate During Placement High ($lb/ft^2/hr$)	Daily Air Temp Low (°C)	Daily Air Temp Low (°F)	Daily Air Temp High (°C)	Daily Air Temp High (°F)	Daily Air Temp Range (°C)	Daily Air Temp Range (°F)
1	Qualification Slab – attempt 2	9/8/2005	-	-	-	-	21	70	31	87	9	17
	Deck – placement 1 (south)	10/14/2005	0.10	0.02	0.29	0.06	11	51	23	74	13	23
	Deck – placement 2 (north)	11/2/2005	0.20	0.04	0.44	0.09	4	39	16	61	12	22
2	Qualification Slab	5/24/2006	-	-	-	-	20	68	30	86	10	18
	Deck	9/13/2006	0.05	0.01	0.10	0.02	12	54	19	67	7	13
Control 1/2	Subdeck (north)	9/30/2005	0.12	0.03	0.59	0.12	6	43	18	65	12	22
	Subdeck (south)	10/18/2005	NR	NR	NR	NR	13	56	28	82	14	26
	SFO (north)	10/10/2005	0.20	0.04	0.29	0.06	6	43	18	64	12	21
	SFO (south)	10/28/2005	0.10	0.02	0.34	0.07	3	37	16	60	13	23
3	Qualification Slab	9/14/2007	Same as LC-HPC-4									
	Deck	11/13/2007	0.07	0.014	0.017	0.034	4	39	19	66	15	27
4	Qualification Slab	9/14/2007	0.13	0.026	0.24	0.05	14	57	29	85	16	28
	Deck – stopped at header	9/29/2007	0.03	0.006	0.15	0.03	13	56	29	84	16	28
	Deck - completed	10/2/2007	0.03	0.007	0.078	0.016	12	54	27	81	15	27
5	Qualification Slab	9/14/2007	Same as LC-HPC-4									
	Deck	11/14/2007	0.11	0.023	0.224	0.046	4	39	19	66	15	27
6	Qualification Slab	9/14/2007	Same as LC-HPC-4									
	Deck	11/3/2007	0.12	0.024	0.30	0.062	2	35	18	65	16	30
Control 3	Subdeck	7/6/2007	0.14	0.028†	-	-	21	70	32	90	11	20
	SFO	7/17/2007	0.20	0.04†	-	-	22	72	33	91	11	19
Control 4	Subdeck	10/20/2007	0.26	0.053†	-	-	10	50	19	67	9	17
	SFO	11/16/2007	NR	NR	-	-	1	33	11	51	10	18

Table D.5b (continued) – Field Information and Site Conditions for LC-HPC and Control Decks

LC-HPC Number	Portion Placed	Date of Placement	Evaporation Rate During Placement				Daily Air Temp					
			Low		High		Low		High		Range	
			($kg/m^2/hr$)	($lb/ft^2/hr$)	($kg/m^2/hr$)	($lb/ft^2/hr$)	(°C)	(°F)	(°C)	(°F)	(°C)	(°F)
Control 5	Subdeck – placement 1 (seq. 1 & 2)	11/8/2008	0.23	0.048†	-	-	0	32	7	44	7	12
	Subdeck – placement 2 (seq. 3, 5, & 6)	11/13/2008	0.43	0.088†	-	-	6	42	11	51	5	9
	Subdeck – placement 3 (seq. 4 & 7)	11/17/2008	0.37	0.076†	-	-	1	33	14	58	14	25
	SFO – placement 1 (west half)	11/22/2008	0.23	0.048†	-	-	-9	16	2	36	11	20
	SFO – placement 2 (east half)	11/25/2008	0.27	0.056†	-	-	-2	29	11	51	12	22
Control 6	Subdeck – placement 1 (seq. 1 & 2)	9/16/2008	0.17	0.035†	-	-	8	47	23	73	14	26
	Subdeck – placement 2 (seq. 3)	9/18/2008	-	-	-	-	13	55	27	80	14	25
	Subdeck – placement 3 (seq. 5 & 6)	9/23/2008	0.26	0.054†	-	-	16	61	26	79	10	18
	Subdeck – placement 4 (seq. 4)	9/26/2008	0.27	0.056†	-	-	15	59	28	82	13	23
	Subdeck – placement 5 (seq. 7)	9/30/2008	-	-	-	-	9	49	23	73	13	24
	SFO – placement 1	10/16/2008	0.28	0.057†	-	-	3	38	13	55	9	17
	SFO – placement 2	10/20/2008	0.23	0.047†	-	-	9	49	22	72	13	23
Control 7	Subdeck – placement 1	3/15/2006	0.35	0.072†	-	-	-2	28	14	57	16	29
	Subdeck – placement 2	8/16/2006	0.32	0.065†	-	-	16	61	31	87	14	26
	SFO – placement 1	3/29/2006	NR	NR	-	-	3	37	12	54	9	17
	SFO – placement 2	9/15/2006	0.28	0.058†	-	-	15	59	30	86	15	27
7	Qualification Slab	6/8/2006	-	-	-	-	17	63	33	91	16	28
	Deck	6/24/2006	0.10	0.02	0.24	0.05	16	60	30	86	14	26

Table D.5b (continued) – Field Information and Site Conditions for LC-HPC and Control Decks

LC-HPC Number	Portion Placed	Date of Placement	Evaporation Rate During Placement				Daily Air Temp					
			Low		High		Low		High		Range	
			($kg/m^2/hr$)	($lb/ft^2/hr$)	($kg/m^2/hr$)	($lb/ft^2/hr$)	(°C)	(°F)	(°C)	(°F)	(°C)	(°F)
8	Qualification Slab	9/26/2007	-	-	-	-	11	52	22	72	11	20
	Deck	10/3/2007	-	-	-	-	8	46	28	83	21	37
9	Qualification Slab – attempt 3 completed	4/1/2009	NR	NR	NR	NR	-2	28	10	50	12	22
	Deck	4/15/2009	0.35	0.072	0.64	0.132	5	41	16	60	11	19
10	Qualification Slab	4/26/2007	-	-	0.20	0.04	-2	29	21	70	23	41
	Deck	5/17/2007	-	-	-	-	8	47	21	69	12	22
Control 8/10	Deck	4/16/2007	-	-	-	-	3	38	18	64	14	26
Control 9	Subdeck	11/3/2007	0.11	0.022	0.61	0.125	-1	30	20	68	21	38
	SFO – placement 1 (east)	5/21/2008	0.14	0.03	0.47	0.097	7	45	23	73	16	28
	SFO – placement 2 (west)	5/29/2008	0.30	0.061	0.10	0.20	13	55	21	70	8	15
11	Qualification Slab	5/25/2007	0.05	0.01	0.15	0.03	10	50	20	68	10	18
	Deck	6/9/2007	0.10	0.02	0.34	0.07	9	48	31	87	22	39
Control 11	Subdeck – placement 1 (North 1/2)	2/3/2006	NR	NR	NR	NR	-4	25	7	45	11	20
	Subdeck – placement 2 (South 1/2)	2/14/2006	NR	NR	NR	NR	-2	28	17	63	19	35
	SFO	3/28/2006	NR	NR	NR	NR	-1	30	17	63	18	33
12	Qualification Slab	3/28/2008					3	37	11	52	8	15
	Deck – phase 1 (east)	4/4/2008	0.05	0.01	0.24	0.05	2	28	16	60	14	32
	Deck – phase 2 (west)	3/18/2009	0.49	0.10	1.07	0.22	7	44	18	64	11	20
Control 12	Subdeck – phase 1 (east)	3/11/2008	NR	NR	NR	NR	-4	25	21	69	25	44
	SFO – phase 1 (east)	4/1/2008	NR	NR	NR	NR	2	36	10	50	12	14
	Subdeck – phase 2 (west)	3/13/2009	-	-	-	-	-1	30	8	46	9	16
	SFO – phase 2 (west)	4/14/2009	-	-	-	-	1	33	18	64	17	31
13	Qualification Slab	4/16/2008	-	-	-	-	7	44	21	69	14	25
	Deck	4/29/2008			0.5	0.1	2	36	15	59	13	23

Table D.5b (continued) – Field Information and Site Conditions for LC-HPC and Control Decks

LC-HPC Number	**Portion Placed**	**Date of Placement**	**Evaporation Rate During Placement**				**Daily Air Temp**					
			Low		High		Low		High		Range	
			(kg/m^2/hr)	(lb/ft^2/hr)	(kg/m^2/hr)	(lb/ft^2/hr)	(°C)	(°F)	(°C)	(°F)	(°C)	(°F)
Control 13	Subdeck	7/11/2008	-	-	-	-	22	72	29	85	7	13
	SFO	7/25/2008	-	-	-	-	24	75	35	95	11	20
14	Qualification Slab	11/13/2007	-	-	0.39	0.08	4	39	19	66	15	27
	Deck placement 1 - Phase 1 attempt 1 (Center)	11/19/2007	-	-	-	-	4	39	16	61	12	22
	Deck placement 1 attempt 2 - Phase 1 (Center)	12/19/2007	0.29	0.06	0.39	0.08	-3	26	8	47	12	21
	Deck placement 2 – Phase 2 (West)	5/2/2008	0.29	0.06	-	-	12	53	28	83	17	30
	Deck placement 3 – Phase 2 (East)	5/21/2008	-	-	-	-	11	52	23	74	12	22
Control Alt	Deck	6/2/2005	-	-	-	-	16	60	25	77	9	17

† Average value, provided by KDOT
NR = Not recorded

Table D.6 – Low-Cracking High Performance Concrete (LC-HPC) Mix Design Information

LC-HPC Number	Portion Placed	Date of Placement	Cement Content (kg/m^3)	Cement Content (lb/yd^3)	*w/cm* ratio	Coarse Aggregate Type	Fine Aggregate Type
1	Qualification Slab – attempt 2	9/8/2005	320	539	0.45	Granite	Natural
	Deck – placement 1 (south)	10/14/2005	320	539	0.45	Granite	Natural
	Deck – placement 2 (north)	11/2/2005	320	539	0.45	Granite	Natural
2	Qualification Slab	5/24/2006	320	539	0.45	Granite	Natural
	Deck	9/13/2006	320	539	0.45	Granite	Natural
Control 1/2	Subdeck (north)	9/30/2005	357	604	0.40	Limestone	Natural
	Subdeck (south)	10/18/2005	359	608	0.40	Limestone	Natural
	SFO (north)	10/10/2005	346 I/II†; 26 SF††	582 I/II†; 44 SF††	0.37	Granite	Natural
	SFO (south)	10/28/2005	346 I/II†; 26 SF††	582 I/II†; 44 SF††	0.37	Granite	Natural
3	Qualification Slab	9/14/2007	Same as LC-HPC-4				
	Deck	11/13/2007	317	535	0.45	Granite	Mfg
4	Qualification Slab	9/14/2007	317	535	0.42	Granite	Mfg
	Deck – stopped at header	9/29/2007	317	535	0.42	Granite	Mfg
	Deck - completed	10/2/2007	317	535	0.42	Granite	Mfg
5	Qualification Slab	9/14/2007	Same as LC-HPC-4				
	Deck	11/14/2007	317	535	0.42	Granite	Mfg
			317	535	0.43	Granite	Mfg
			317	535	0.43	Granite	Mfg
			317	535	0.45	Granite	Mfg
6	Qualification Slab	9/14/2007	Same as LC-HPC-4				
	Deck	11/3/2007	317	535	0.45	Granite	Mfg
Control 3	Subdeck	7/6/2007	318 I/II†; 79 FA†††	535 I/II†; 133 FA†††	0.40	Granite	Natural

Table D.6 (continued) – Low-Cracking High Performance Concrete (LC-HPC) Mix Design Information

LC-HPC Number	Portion Placed	Date of Placement	Cement Content (kg/m^3)	Cement Content (lb/yd^3)	*w/cm* ratio	Coarse Aggregate Type	Fine Aggregate Type
Control 3 Continued	SFO	7/17/2007	346 I/II†; 26 SF††	582 I/II†; 44 SF††	0.37	Granite	Natural
Control 4	Subdeck	10/20/2007	318 I/II†; 79 FA†††	535 I/II†; 133 FA†††	0.40	Granite	Natural
	SFO	11/16/2007	346 I/II†; 26 SF††	582 I/II†; 44 SF††	0.37	Granite	Natural
Control 5	Subdeck – placement 1 (seq. 1 & 2)	11/8/2008	318 I/II†; 79 FA†††	535 I/II†; 133 FA†††	0.40	Granite	Natural
	Subdeck – placement 2 (seq. 3, 5, & 6)	11/13/2008	318 I/II†; 79 FA†††	535 I/II†; 133 FA†††	0.40	Granite	Natural
	Subdeck – placement 3 (seq. 4 & 7)	11/17/2008	318 I/II†; 79 FA†††	535 I/II†; 133 FA†††	0.40	Granite	Natural
	SFO – placement 1 (west half)	11/22/2008	346 I/II†; 26 SF††	582 I/II†; 44 SF††	0.37	Granite	Natural
	SFO – placement 2 (east half)	11/25/2008	346 I/II†; 26 SF††	582 I/II†; 44 SF††	0.37	Granite	Natural
Control 6	Subdeck – placement 1 (seq. 1 & 2)	9/16/2008	318 I/II†; 79 FA†††	535 I/II†; 133 FA†††	0.40	Granite	Natural
	Subdeck – placement 2 (seq. 3)	9/18/2008	318 I/II†; 79 FA†††	535 I/II†; 133 FA†††	0.40	Granite	Natural
	Subdeck – placement 3 (seq. 5 & 6)	9/23/2008	318 I/II†; 79 FA†††	535 I/II†; 133 FA†††	0.40	Granite	Natural
	Subdeck – placement 4 (seq. 4)	9/26/2008	318 I/II†; 79 FA†††	535 I/II†; 133 FA†††	0.40	Granite	Natural
	Subdeck – placement 5 (seq. 7)	9/30/2008	318 I/II†; 79 FA†††	535 I/II†; 133 FA†††	0.40	Granite	Natural
	SFO – placement 1	10/16/2008	346 I/II†; 26 SF††	582 I/II†; 44 SF††	0.37	Granite	Natural

Table D.6 (continued) – Low-Cracking High Performance Concrete (LC-HPC) Mix Design Information

LC-HPC Number	Portion Placed	Date of Placement	Cement Content (kg/m³)	Cement Content (lb/yd³)	*w/cm* ratio	Coarse Aggregate Type	Fine Aggregate Type
Control 6 Continued	SFO – placement 2	10/20/2008	346 I/II[†]; 26 SF[††]	582 I/II[†]; 44 SF[††]	0.37	Granite	Natural
7	Qualification Slab	6/8/2006	320	539	0.45	Granite	Natural
	Deck	6/24/2006	320	539	0.45	Granite	Natural
Control 7	Subdeck – placement 1	3/15/2006	318 I/II[†]; 79 FA[†††]	535 I/II[†]; 132 FA[†††]	0.40	Granite	Natural
	Subdeck – placement 2	8/16/2006	318 I/II[†]; 79 FA[†††]	535 I/II[†]; 132 FA[†††]	0.40	Granite	Natural
	SFO – placement 1	3/29/2006	346 I/II[†]; 26 SF[††]	582 I/II[†]; 44 SF[††]	0.37	Granite	Natural
	SFO – placement 2	9/15/2006	346 I/II[†]; 26 SF[††]	582 I/II[†]; 44 SF[††]	0.37	Granite	Natural
8	Qualification Slab	6/8/2006	317	535	0.42	Granite	Natural
	Deck	10/3/2007	317	535	0.42	Granite	Natural
9	Qualification Slab – attempt 1	3/23/2009	320	539	0.43	Granite	Natural
	Qualification Slab – attempt 2	3/25/2009	320	539	0.44	Granite	Natural
	Qualification Slab – attempt 3 completed	4/1/2009	320	539	0.44	Granite	Natural
	Deck	4/15/2009	320	539	0.44	Granite	Natural
10	Qualification Slab	4/26/2007	317	535	0.42	Granite	Natural
	Deck	5/17/2007	317	535	0.40-0.42; 0.41 average	Granite	Natural
Control 8/10	Deck	4/16/2007	363	611	0.40	Limestone	Natural
Control 9	Subdeck	11/3/2007	363	611	0.40	Limestone	Natural
	SFO – placement 1 (east)	5/21/2008	350 I/II[†]; 26 SF[††]	589 I/II[†]; 44 SF[††]	0.37	Quartzite	Natural

Table D.6 (continued) – Low-Cracking High Performance Concrete (LC-HPC) Mix Design Information

LC-HPC Number	Portion Placed	Date of Placement	Cement Content (kg/m³)	Cement Content (lb/yd³)	*w/cm* ratio	Coarse Aggregate Type	Fine Aggregate Type
Control 9 Continued	SFO – placement 2 (west)	5/29/2008	350 I/II†; 26 SF††	589 I/II†; 44 SF††	0.37	Quartzite	Natural
11	Qualification Slab	5/25/2007	317	534	0.42	Granite	Natural
	Deck	6/9/2007	317	534	0.42	Granite	Natural
Control 11	Subdeck – placement 1 (North 1/2)	2/3/2006	357	600	0.40	Limestone	Natural
	Subdeck – placement 2 (South 1/2)	2/14/2006	357	600	0.40	Limestone	Natural
	SFO	3/28/2006	346 I/II†; 26 SF††	581 I/II†; 44 SF††	0.37	Quartzite	Natural
12	Qualification Slab	3/28/2008	320	540	0.45	Granite	Natural
	Deck – phase 1 (east)	4/4/2008	320	540	0.44	Granite	Natural
	Deck – phase 2 (west)	3/18/2009	317	535	0.45	Granite	Natural
			317	535	0.44	Granite	Natural
Control 12	Subdeck – phase 1 (east)	3/11/2008	358	602	0.44	Limestone	Natural
	SFO - phase 1 (east)	4/1/2008	345 I/II†; 26 SF††	581 I/II†; 44 SF††	0.37	Quartzite	Natural
	Subdeck – phase 2 (west)	3/13/2009	358	602	0.44	Limestone	Natural
	SFO - phase 2 (west)	4/14/2009	345 I/II†; 26 SF††	581 I/II†; 44 SF††	0.37	Quartzite	Natural
13	Qualification Slab	4/16/2008	320	540	0.44	Granite	Natural
	Deck	4/29/2008	317	535	0.44	Granite	Natural
Control 13	Subdeck	7/11/2008	363	611	0.40	Limestone	Natural
	SFO	7/25/2008	350 I/II†; 26 SF††	589 I/II†; 44 SF††	0.37	Quartzite	Natural
14	Qualification Slab	11/13/2007	317	535	0.45	Granite	Mfg
			317	535	0.42	Granite	Mfg

Table D.6 (continued) – Low-Cracking High Performance Concrete (LC-HPC) Mix Design Information

LC-HPC Number	Portion Placed	Date of Placement	Cement Content (kg/m^3)	Cement Content (lb/yd^3)	*w/cm* ratio	Coarse Aggregate Type	Fine Aggregate Type
14 Continued	Deck placement 1 - Phase 1 attempt 1 (Center)	11/19/2007	317	535	0.42	Granite	Mfg
	Deck placement 1 attempt 2 - Phase 1 (Center)	12/19/2007	317	535	0.45	Granite	Mfg
	Deck placement 2 - Phase 2 (West)	5/2/2008	317	535	0.45	Granite	Mfg
	Deck placement 3 - Phase 2 (East)	5/21/2008	317	535	0.45	Granite	Mfg
Control Alt	Deck	6/2/2005	357	602	0.40	Limestone	Natural

† I/II = Type I/II cement

†† SF = Silica fume

FA††† = Fly Ash

Table D.7 – Low-Cracking High-Performance Concrete (LC-HPC) and Control Deck Average Concrete Properties

LC-HPC Number	Portion Placed	Date of Placement	Average Air Content (%)	Average Slump (mm)	Average Slump (in)	Average Concrete Temp (°C)	Average Concrete Temp (°F)	Average Compressive Strength (MPa)	Average Compressive Strength (psi)
1	Qualification Batch	6/23/2005	6.5	63	2.5	32	89	35.1 (15 days) 39.5 (28 days)	5090 (15 days) 5730 (28 days)
	Qualification Slab – attempt 1		-	-	-	26	78	-	-
	Qualification Slab – attempt 2	9/8/2005	8.4	74	2.9	20	68	-	-
	Deck – placement 1 (south)	10/14/2005	7.9	96	3.8	20	68	35.9	5210
	Deck – placement 2 (north)	11/2/2005	7.7	83	3.3	20	68	34.4	4980
2	Qualification Batch	6/23/2005	Same as LC-HPC-1						
	Qualification Slab	5/24/2006	7.8	117	4.6	21	70	27.4	3970
	Deck	9/13/2006	7.7	77	3.0	19	67	31.7	4600
Control 1/2	Subdeck (north)	9/30/2005	5.25	110	4.3	21	70	39.1	5670
	Subdeck (south)	10/18/2005	6.5	81	3.2			35.1	5090
	SFO (north)	10/10/2005	5.5	125	5.0	20	68	40.1	5810
	SFO (south)	10/28/2005	7	115	4.5	17	63	55.6	8060
3	Qualification Batch	6/7/2007	Same as LC-HPC-4						
	Qualification Slab	9/14/2007	Same as LC-HPC-4						
	Deck	11/13/2007	8.6	83	3.3	58††	14††	41.3	5990
4	Qualification Batch	6/7/2007 "KU Mix"	9.6	100	4.0	22	71	-	-
		6/7/2007 "Alternate Mix"	9.5	125	5.0	22	72	-	-
	Qualification Slab	9/14/2007	6.3	39	1.5	18	64	-	-
	Deck – stopped at header	9/29/2007	8.5	47	1.9	NR	NR	NR	NR

Table D.7 (continued) – Low-Cracking High-Performance Concrete (LC-HPC) and Control Deck Average Concrete Properties

LC-HPC Number	Portion Placed	Date of Placement	Average Air Content	Average Slump		Average Concrete Temp		Average Compressive Strength	
			(%)	(mm)	(in)	(°C)	(°F)	(MPa)	(psi)
4 Continued	Deck - completed	10/2/2007	8.6	78	3.1	17††	63††	33.1	4790
5	Qualification Batch	6/7/2007	Same as LC-HPC-4						
	Qualification Slab	9/14/2007	Same as LC-HPC-4						
	Deck	11/14/2007	8.7	80	3.1	16††	61††	44.0	6380
6	Qualification Batch	6/7/2007	Same as LC-HPC-4						
	Qualification Slab	9/14/2007	Same as LC-HPC-4						
	Deck	11/3/2007	9.5	96	3.8	15††	60††	40.3	5840
Control 3	Subdeck	7/6/2007	5.8	169	6.7	27.1	81	39.2	5680
	SFO	7/17/2007	6.7	185	7.3	29.9	86	57.6	8350
Control 4	Subdeck	10/20/2007	7.3	195	7.7	22.8	73	43.7	6340
	SFO	11/16/2007	6.9	147	5.8	20.0	68	53.1	7700
Control 5	Subdeck – placement 1 (seq. 1 & 2)	11/8/2008	5.6	200	8.0	14	58	NR	NR
	Subdeck – placement 2 (seq. 3, 5, & 6)	11/13/2008	6.8	232	9.1	21	70	NR	NR
	Subdeck – placement 3 (seq. 4 & 7)	11/17/2008	5.4	206	8.1	18	64	NR	NR
	SFO – placement 1 (west half)	11/22/2008	7.6	150	6.0	12	53	58.7	8510
	SFO – placement 2 (east half)	11/25/2008	6.6	230	9.1	17	62.5	NR	NR
Control 6	Subdeck – placement 1 (seq. 1 & 2)	9/16/2008	7.4	206	8.1	23	73.5	34.1	4940
	Subdeck – placement 2 (seq. 3)	9/18/2008	-	-	-	-	-	-	-

Table D.7 (continued) – Low-Cracking High-Performance Concrete (LC-HPC) and Control Deck Average Concrete Properties

LC-HPC Number	Portion Placed	Date of Placement	Average Air Content (%)	Average Slump (mm)	Average Slump (in)	Average Concrete Temp (°C)	Average Concrete Temp (°F)	Average Compressive Strength (MPa)	Average Compressive Strength (psi)
Control 6 Continued	Subdeck – placement 3 (seq. 5 & 6)	9/23/2008	6.4	173	7.0	26	79.5	NR	NR
	Subdeck – placement 4 (seq. 4)	9/26/2008	6.6	158	6.2	29.2	84.5	NR	NR
	Subdeck – placement 5 (seq. 7)	9/30/2008	-	-	-	-	-	-	-
	SFO – placement 1	10/16/2008	7.7	175	7.0	22	71.8	53.1	7700
	SFO – placement 2	10/20/2008	8.1	210	8.4	23	73	NR	NR
Control 7	Subdeck – placement 1	3/15/2006	7.3	195	7.75	21.3	70	37.9	-
	Subdeck – placement 2	8/16/2006	5.9	235	9.25	26.5	80	38.2	-
	SFO – placement 1	3/29/2006	6.4	95	3.75	18	64	50.8	-
	SFO – placement 2	9/15/2006	7.9	195	7.75	23	73	NR	-
7	Qualification Batch	5/31/2006	6.5	95	3.75	23	73	23.9* Slump high	3460* Slump high
	Qualification Slab	6/8/2006	8.0	70	2.75	-	-	22.4 (5 days)	3250 (5 days)
	Deck	6/24/2006	8.0	91	3.6	$22^{\dagger\dagger}$	$71^{\dagger\dagger}$	26.1 (31 days)	3780 (31 days)
8	Qualification Batch	4/11/2007	8.3	44	1.75	13	59	29.2	4230
	Qualification Slab	9/26/2007	7.0	45	1.75	19	66	29.7	4310
	Deck	10/3/2007	8.0	54	2.1	19.5	67	32.7	4730
9	Qualification Batch	3/25/2009	9.2	90	3.5	16	60	-	-
	Qualification Slab – attempt 1	3/23/2009	7.1	41	1.6	26	78	NR	NR
	Qualification Slab – attempt 2	3/25/2009	9.2	90	3.5	16	60	NR	NR

Table D.7 (continued) – Low-Cracking High-Performance Concrete (LC-HPC) and Control Deck Average Concrete Properties

LC-HPC Number	Portion Placed	Date of Placement	Average Air Content (%)	Average Slump (mm)	Average Slump (in)	Average Concrete Temp (°C)	Average Concrete Temp (°F)	Average Compressive Strength (MPa)	Average Compressive Strength (psi)
9 Continued	Qualification Slab – attempt 3 completed	4/1/2009	8.8	99	3.9	14	58	23.1	3350
	Deck	4/15/2009	6.7	86	3.4	18	64	28.9 (30 days)	4190 (30 days)
10	Qualification Batch	4/11/2007	8.3	44	1.75	13	59	29.2	4230
	Qualification Slab	4/26/2007	8.7	91	3.6	21	70	28.2	4090
	Deck	5/17/2007	7.5	80	3.1	18.3	65	31.6	4580
Control 8/10	Deck	4/16/2007	7.4	137	5.4	21	70	33.3	4830
Control 9	Subdeck	11/3/2007	6.2	67	2.6	19	66	33.5	4850
	SFO – placement 1 (east)	5/21/2008	6.2	193	7.6	19	60.5	42.6	6170
	SFO – placement 2 (west)	5/29/2008	5.6	90	3.5	25	77	44.0	6380
11	Qualification Batch - 1	5/23/2007	7.9	80	3.1	25	77	-	-
	Qualification Batch - 2	6/7/2007	7.8	80	3.1	21.4	70.5	-	-
	Qualification Slab	5/25/2007	7.2	106	4.2	18	65	35.2 (6 days)	5100 (6 days)
	Deck	6/9/2007	7.6	79	3.1	16	61	23.9 (9 days) 27.1 (16 days) 32.3 (27 days)	3470 (9 days) 3930 (16 days) 4680 (27 days)
Control 11	Subdeck – placement 1 (North 1/2)	2/3/2006	7.2	90	3.5	22	72	38.7	5610
	Subdeck – placement 2 (South 1/2)	2/14/2006	7.0	103	4.1	23	73	36.4	5280
	SFO	3/28/2006	6.0	78	3.1	15.5	60	52.7	7640
12	Qualification Batch – phase 1	3/25/2008	8.0	100	4.0	18	65	-	-

Table D.7 (continued) – Low-Cracking High-Performance Concrete (LC-HPC) and Control Deck Average Concrete Properties

LC-HPC Number	Portion Placed	Date of Placement	Average Air Content	Average Slump		Average Concrete Temp		Average Compressive Strength	
			(%)	(mm)	(in)	(°C)	(°F)	(MPa)	(psi)
12 Continued	Qualification Slab	3/28/2008	7.9	94	3.7	14	57	33.0	4780
	Deck – phase 1 (east)	4/4/2008	7.4	70	2.75	14	57	31.5	4570
	Qualification Batch – phase 2	3/12/2009	7.0	95	3.75	16	61	-	-
	Deck – phase 2 (west)	3/18/2009	7.8	104	4.1	19	67	28.8 (0.45 *w/c*) 31.6 (0.44 *w/c*)	4180 (0.45 *w/c*) 4580 (0.44 *w/c*)
Control 12	Subdeck – phase 1 (east)	3/11/2008	6.9	110	4.3	23	74	33.3	4830
	SFO – phase 1 (east)	4/1/2008	6.8	92	3.6	15	59	43.1	6240
	Subdeck – phase 2 (west)	3/13/2009	7.2	120	4.7	22	72	34.3 (31 days)	4980 (31 days)
	SFO – phase 2 (west)	4/14/2009	7.7	57	2.25	17	62	53.1	7710
13	Qualification Slab	4/16/2008	6.2	112	4.4	23	73	-	-
	Deck	4/29/2008	8.0	75	3.0	21	70	29.5	4280
Control 13	Subdeck	7/11/2008	5.8	91	3.6	32	89	-	-
	SFO	7/25/2008	6.3	133	5.2	33	91	57.1	8280
14	Qualification Slab	11/13/2007	7.6	75	3.0	20.6	69	-	-
	Deck placement 1 - Phase 1 attempt 1 (Center)	11/19/2007	-	-	-	-	-	-	-
	Deck placement 1 attempt 2 - Phase 1 (Center)	12/19/2007	8.7	91	3.6	18	65	30.6	4440
	Deck placement 2 - Phase 2 (West)	5/2/2008	9.8	109	4.3	18	64	25.6	3710
	Deck placement 3 - Phase 2 (East)	5/21/2008	9.7	132	5.2	18	65	26.4	3830

Table D.7 (continued) – Low-Cracking High-Performance Concrete (LC-HPC) and Control Deck Average Concrete Properties

LC-HPC Number	Portion Placed	Date of Placement	Average Air Content	Average Slump		Average Concrete Temp		Average Compressive Strength	
			(%)	(mm)	(in)	(°C)	(°F)	(MPa)	(psi)
Control Alt	Deck	6/2/2005	5.9	75	3.0	-	-	38.0	5510

† Prestressed concrete girders.

NR = Not recorded.

* Cylinders made from a batch with 165 mm slump and 7.0% air content. This is not the qualified batch.

†† Surface temperature measured with infrared thermometer.

Table D.8 – Individual Plastic Concrete Test Results for LC-HPC and Control Bridge Decks

Truck	Air Content	Slump		Concrete Temperature†		Concrete Surface Temperature††		Location of Sample	Notes
	(%)	(mm)	(in)	(°C)	(°F)	(°C)	(°F)		
LC-HPC-1 (105-304) Qualification Slab, Cast on 9/8/2005									
1	8.2	185	7.25	21	70	21	70	-	Truck rejected
2	8.8	90	3.5	22	71	-	-	-	-
3	7.7	53	2.25	20	68	-	-	-	-
4	9.2	100	4.0	19	67	-	-	-	-
5	7.7	53	2.25	21	69	-	-	-	-
LC-HPC-1 (105-304) Placement 1, Cast on 10/14/2005									
1	7.5	95	3.75	18	64	19	66	-	Air Temp = 11° C
2	6.2	85	3.25	16	60	19	67	-	Air Temp = 12° C
3	8.0	65	2.5	22	71	20	68	-	Air Temp = 13° C
7	9.0	95	3.75	19	66	17	63	-	Air Temp = 14° C
10	11.5	165	6.5	19	66	19	67	-	Placed in deck at Sta. 4+990 (15 m from east abutment)
11	6.0	90	3.5	20	68	20	68	-	Air Temp = 15° C
15	7.5	90	3.5	22	71	20	68	-	Air Temp = 15° C
21	7.4	85	3.25	22	71	20	69	-	Air Temp = 15° C
LC-HPC-1 (105-304) Placement 2, Cast on 11/2/2005									
1	7.0	108	4.25	19	66	19	66		Air Temp = 11° C
2	6.5	75	3	20	68	20	68		Air Temp = 11° C
3	3.0	64	2.5	20	68	19	67		Air Temp = 12° C
4	9.0	95	3.75	19	66	16	60		Air Temp = 13° C
8	9.0	90	3.5	21	69	18	65		Air Temp = 14° C
12	8.0	64	2.5	19	66	18	65		Air Temp = 15° C
16	8.5	100	4.0	20	68	21	70		Air Temp = 20° C
20	9.0	90	3.5	19	66	18	65		Air Temp = 13° C
24	9.0	70	2.75	21	69	19	67		Air Temp = 14° C
26	8.5	90	3.5	20	68	19	67		Air Temp = 20° C

Table D.8 (continued) – Individual Plastic Concrete Test Results for LC-HPC and Control Bridge Decks

Truck	Air Content	Slump		Concrete Temperature†		Concrete Surface Temperature††		Location of Sample	Notes
	(%)	(mm)	(in)	(°C)	(°F)	(°C)	(°F)		
LC-HPC-2 (105-310), Cast on 9/13/2006									
-	7.0	100	4	-	-	18.9	66		
-	8.5	93	3.75	-	-	20.6	69		
-	7.2	80	3.25	-	-	19.4	67		
-	7.2	85	3.25	-	-	18.3	65		
-	7.5	80	3.25	-	-	17.5	64		
-	8.0	65	2.5	-	-	20.3	69		
-	8.5	33	1.25	-	-	18.9	66		
Control 1/2 , North ½ Silica Fume, Cast on 10/10/2005									
-	5.5	125	5	18	64				
Control 1/2 , South ½ Bridge Deck, Cast on 10/18/2005									
-	7	88	3.5	24	75				
-	6	75	3	25	77				
-	6.5	80	3.25	25	77				
Control 1/2 , North ½ Bridge Deck, Cast on 9/30/2005									
-	5	120	4.75	18	64				
-	5.5	100	4	20	68				
Control 1/2 , South ½ Silica Fume, Cast on 10/28/2005									
-	7	115	4.5	20	68				
LC-HPC-3,4,5 and 6 (46-338, 46-339, 46-340, and 46-340 Units 1 and 2) Qualification Slab, Cast on 9/14/2007									
1	7	72	2.75	18.5	65				Out of truck, Fordyce
1	8	70	2.75	18	64				After pump, Fordyce
2	7	53	2	17	63				Out of truck, Fordyce
3	6.9	40	1.5	17	63				Out of truck, KU-Mix
3	7	43	1.75	19.5	67				After pump, KU-Mix
4	5.6	34	1.25	16.5	62				Out of truck, KU-Mix
LC-HPC-3 (46-338) Deck, Cast on 11/13/2007									
1	9.1	135	5.25	-	-	15	59	-	Wait and retest

Table D.8 (continued) – Individual Plastic Concrete Test Results for LC-HPC and Control Bridge Decks

Truck	Air Content (%)	Slump (mm)	Slump (in)	Concrete Temperature† (°C)	Concrete Temperature† (°F)	Concrete Surface Temperature†† (°C)	Concrete Surface Temperature†† (°F)	Location of Sample	Notes
1	-	65	2.5	-	-	-	-	-	Retest
2	7.8	45	1.75	-	-	13	56	-	6% after pump, 1.8% loss
3	8.2	52	2.0	-	-	16	60	-	-
4	-	-	-	-	-	17	62	-	-
5	-	78	3.0	-	-	15	59	-	-
6	-	-	-	-	-	14	57	-	-
7	9.1	65	2.5	-	-	16	61	-	-
8	-	-	-	-	-	11	52	-	-
9	-	82	3.25	-	-	16	61	-	-
10	-	-	-	-	-	12	54	-	-
11	7.0	71	2.75	-	-	15	59	-	-
12	-	-	-	-	-	11	52	-	-
13	-	70	2.75	-	-	15	59	-	-
14	-	-	-	-	-	12	54	-	-
15	9.2	-	-	-	-	13	55	-	Retested – Originally 12.0% air and 100 mm slump
16	9.0	-	-	-	-	16	60	-	-
17	-	85	3.25	-	-	15	59	-	-
18	-	-	-	-	-	12	53	-	-
19	6.5	60	2.25	-	-	15	59	-	-
20	-	-	-	-	-	11	52	-	-
21	-	-	-	-	-	14	57	-	-
22	-	-	-	-	-	14	58	-	-
23	9.5	100	4.0	-	-	13	56	-	8.4% after pump – 1.1% loss
24	-	-	-	-	-	14	58	-	-
25	-	100	4.0	-	-	14	58	-	-
26	-	-	-	-	-	16	60	-	-

Table D.8 (continued) – Individual Plastic Concrete Test Results for LC-HPC and Control Bridge Decks

Truck	**Air Content** (%)	**Slump** (mm)	(in)	**Concrete Temperature**† (°C)	(°F)	**Concrete Surface Temperature**†† (°C)	(°F)	**Location of Sample**	**Notes**
27	-	93	3.75	-	-	15	59	-	Retested – originally 9% air and 120 mm slump
28	-	-	-	-	-	14	58	-	-
29	-	100	4.0	-	-	13	55	-	-
30	-	-	-	-	-	14	57	-	-
31	8.0	70	2.75	-	-	13	56	-	-
32	-	-	-	-	-	15	59	-	-
33	-	97	3.75	-	-	14	57	-	-
34	-	-	-	-	-	13	56	-	-
35	7.8	90	3.5	-	-	16	60	-	-
36	-	-	-	-	-	16	61	-	-
37	-	92	3.5	-	-	16	60	-	Retested – originally 160 mm slump
38	-	-	-	-	-	14	58	-	-
39	-	100	4.0	-	-	16	60	-	Retested – originally 8.2% air and 135 mm slump
40	-	100	4.0	-	-	14	58	-	-
41	-	89	3.5	-	-	15	59	-	-
42	-	-	-	-	-	13	56	-	-
43	9.5	89	3.5	-	-	16	60	-	-
44	-	-	-	-	-	14	58	-	-
45	-	85	3.25	-	-	14	57	-	-
46	-	-	-	-	-	15	59	-	-
47	10.5	82	3.25	-	-	16	60	-	8.4% after pump – 1.5% loss
48	-	-	-	-	-	16	61	-	-
49	-	88	3.5	-	-	14	58	-	-
50	-	-	-	-	-	14	57	-	-
51	10.0	98	3.75	-	-	16	60	-	-

Table D.8 (continued) – Individual Plastic Concrete Test Results for LC-HPC and Control Bridge Decks

Truck	Air Content (%)	Slump (mm)	Slump (in)	Concrete Temperature† (°C)	Concrete Temperature† (°F)	Concrete Surface Temperature†† (°C)	Concrete Surface Temperature†† (°F)	Location of Sample	Notes
LC-HPC-4 (46-339) Deck stopped at header, Cast on 9/29/2007									
-	7	30	1.25	-	-	-	-	-	Tested after pump
-	7.6	56	2.25	-	-	-	-	-	Tested after mid range
1	7.8	30	1.25	-	-	-	-	-	Tested from truck
2	6.8	18	0.75	-	-	-	-	-	-
3	10.4	100	4	-	-	-	-	-	Rejected high air, low weight
4	6.8	48	2	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-	-
6	-	35	1.5	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-	-
8	7.4	19	0.75	-	-	-	-	-	-
9	-	-	-	-	-	-	-	-	-
10	-	20	0.75	-	-	-	-	-	-
11	-	-	-	-	-	-	-	-	-
12	11.4	97	3.75	-	-	-	-	-	Rejected high air, low weight
13	-	-	-	-	-	-	-	-	-
14	-	-	-	-	-	-	-	-	-
15	-	60	2.25	-	-	-	-	-	5 yards waste
16	-	-	-	-	-	-	-	-	5 yards waste
17	11.8	120	4.75	-	-	-	-	-	Accepted to reach header
-	11.6	103	4	-	-	-	-	-	Accepted to reach header
18	8.8	-	-	-	-	-	-	-	Accepted to reach header
19	10.6	90	3.5	-	-	-	-	-	Accepted to reach header
LC-HPC-4 (46-339) Deck completed, Cast on 10/2/2007									
1	8.8	65	2.5	-	-	18.3	65	-	Truck
-	6.8	65	2.5	-	-	16.7	62	-	Pump
2	7.2	38	1.5	-	-	17.2	63	-	-
3	7.8	45	1.75	-	-	-	-	-	-

Table D.8 (continued) – Individual Plastic Concrete Test Results for LC-HPC and Control Bridge Decks

Truck	Air Content	Slump		Concrete Temperature†		Concrete Surface Temperature††		Location of Sample	Notes
	(%)	(mm)	(in)	(°C)	(°F)	(°C)	(°F)		
4	-	-	-	-	-	18.9	66	-	-
5	-	35	1.5	-	-	17.2	63	-	-
6	-	-	-	-	-	19.4	67	-	-
7	10.4	80	3.25	-	-	17.8	64	-	-
8	-	-	-	-	-	16.7	62	-	-
9	-	90	3.5	-	-	15.0	64	-	-
10	-	-	-	-	-	16.1	59	-	-
11	9.5	100	4	-	-	16.7	61	-	-
12	-	-	-	-	-	16.7	62	-	-
13	-	100	4	-	-	16.7	62	-	-
14	-	-	-	-	-	16.7	62	-	-
15	9.8	90	3.5	-	-	16.7	62	-	-
16	-	-	-	-	-	16.7	62	-	-
17	-	55	2.25	-	-	16.7	62	-	-
18	-	-	-	-	-	15.6	60	-	-
19	9.6	100	4	-	-	15.6	60	-	-
20	-	-	-	-	-	17.2	63	-	-
21	-	100	4	-	-	17.2	63	-	-
22	-	-	-	-	-	17.8	64	-	-
23	8.8	88	3.5	-	-	18.3	65	-	-
24	-	-	-	-	-	17.8	64	-	-
25	-	75	3	-	-	17.8	64	-	-
26	-	-	-	-	-	20.0	68	-	-
27	7.9	95	3.75	-	-	17.2	66	-	-
28	-	-	-	-	-	17.2	63	-	-
29	-	100	4	-	-	17.2	63	-	-
30	9.3	90	3.5	-	-	18.9	64	-	-
31	-	-	-	-	-	18.9	66	-	-

Table D.8 (continued) – Individual Plastic Concrete Test Results for LC-HPC and Control Bridge Decks

Truck	Air Content	Slump		Concrete Temperature†		Concrete Surface Temperature††		Location of Sample	Notes
	(%)	(mm)	(in)	(°C)	(°F)	(°C)	(°F)		
32	-	95	3.75	-	-	18.3	65	-	-
33	-	-	-	-	-	15.6	60	-	-
34	8	35	1.5	-	-	18.3	65	-	-
LC-HPC-5 (46-340), Cast on 11/14/2007									
1	11	138	5.5	18	64	18	64	-	Held b/c of high slump and air
2	7	92	3.5	15	59	15	59	Truck	Taken before the pump
1R	8	70	2.75	-	-	-	-	-	-
2	7.4	62	2.5	-	-	-	-	Deck	Taken after the pump, 5 cylinders were made
3	9.5	75	3	16	61	16	61	-	-
4	-	-	-	16.5	62	16.5	62	-	-
5	-	60	2.25	17	63	17	63	-	-
6	-	-	-	16	61	16	61	-	Pump got stuck at 3:44,4:03,4:12
7	8.7	50	2	18	64	18	64	-	-
8	-	-	-	16.5	62	16.5	62	-	Slow pumping
9	-	65	2.5	16	61	16	61	-	Slow pumping
10	-	-	-	18	64	18	64	-	-
11	9	60	2.25	17	63	17	63	-	-
12	-	-	-	16	61	16	61	-	-
13	-	60	2.25	16.5	62	16.5	62	-	-
14	-	-	-	14	57	14	57	-	-
15	9	60	2.25	16.5	62	16.5	62	-	-
16	8.5	65	2.5	15.5	60	15.5	60	-	Switched from 0.42 to 0.43 w/c
17	-	102	4	14.5	58	14.5	58	-	-
18	-	-	-	14.5	58	14.5	58	-	-
19	10.3	100	4	16	61	16	61	-	-
20	-	-	-	15	59	15	59	-	-

Table D.8 (continued) – Individual Plastic Concrete Test Results for LC-HPC and Control Bridge Decks

Truck	Air Content	Slump		Concrete Temperature†		Concrete Surface Temperature††		Location of Sample	Notes
	(%)	(mm)	(in)	(°C)	(°F)	(°C)	(°F)		
21	-	140	5.5	16	61	16	61	-	-
22	-	95	3.75	16	61	16	61	-	-
21R	8.5	100	4	16	61	16	-	-	-
23	-	-	-	14	57	14	57	-	-
24	-	-	-	15	59	15	59	-	-
25	-	65	2.5	16	61	16	61	-	-
26	-	-	-	14	57	14	57	-	-
27	6.8	59	2.25	16	61	16	61	-	Switched from 0.43 to 0.45 w/c
28	-	-	-	15	59	15	59	-	-
29	-	80	3.25	16.5	62	16.5	62	-	-
30	-	-	-	16	61	16	61	-	-
31	9	100	4	16.5	62	16.5	62	-	-
32	-	-	-	15	59	15	59	-	-
33	-	80	3.25	14	57	14	57	-	-
34	-	-	-	15.5	60	15.5	60	-	-
35	8.8	74	3	16	61	16	61	-	-
36	-	-	-	15.5	60	15.5	60	-	-
37	-	95	3.75	16	61	16	61	-	-
38	-	-	-	15	59	15	59	-	-
39	9	83	3.25	15.5	60	15.5	60	-	-
40	-	-	-	14.5	58	14.5	58	-	-
41	-	95	3.75	16	61	16	61	-	-
42	-	-	-	16.5	62	16.5	62	-	-
43	8.5	80	3.25	14.5	58	14.5	58	-	-
44	-	-	-	15	59	15	59	-	-
45	-	74	3	16.5	62	16.5	62	-	-
46	-	-	-	15.5	60	15.5	60	-	-
47	10.2	85	3.25	17	63	17	63	-	-

Table D.8 (continued) – Individual Plastic Concrete Test Results for LC-HPC and Control Bridge Decks

Truck	Air Content (%)	Slump (mm)	Slump (in)	Concrete Temperature† (°C)	Concrete Temperature† (°F)	Concrete Surface Temperature†† (°C)	Concrete Surface Temperature†† (°F)	Location of Sample	Notes
48	-	73	2.75	17	63	17	63	-	-
LC-HPC-6 (46-340), Cast on 11/3/2007									
1	9.9	107	425	12.8	55	12.8	55	-	-
-	7	55	2.25	-	-	-	-	-	Drop 2.9 % after pump
2	11.5	120	4.75	-	-	11.1	52	-	Truck 2 being tested
3	-	-	-	-	-	11.7	53	-	-
4	-	-	-	-	-	12.2	54	-	Test top 6% air
5	-	80	3.25	-	-	15.6	60	-	Test top 7%
6	-	-	-	-	-	12.8	55	-	-
7	8.4	75	3	-	-	13.3	56	-	-
8	-	-	-	-	-	12.7	55	-	-
9	-	60	2.25	-	-	12.7	55	-	-
10	-	-	-	-	-	14.4	58	-	-
11	9.1	70	2.75	-	-	13.9	57	-	-
12	-	-	-	-	-	14.4	58	-	-
13	-	72	2.75	-	-	15.6	60	-	36F air, concrete 55F
14	-	-	-	-	-	15.0	59	-	-
15	10.5	100	4	-	-	14.4	58	-	-
16	-	-	-	-	-	15.6	60	-	-
17	-	103	4	-	-	12.2	54	-	-
18	-	-	-	-	-	16.1	61	-	-
19	10.2	105	4.25	-	-	16.1	61	-	-
20	-	-	-	-	-	15.6	60	-	-
21	-	80	3.25	-	-	16.7	62	-	-
22	-	-	-	-	-	15.6	60	-	-
23	7.5	92	3.5	-	-	16.7	62	-	-
24	-	-	-	-	-	16.7	62	-	-

Table D.8 (continued) – Individual Plastic Concrete Test Results for LC-HPC and Control Bridge Decks

Truck	Air Content	Slump		Concrete Temperature†		Concrete Surface Temperature††		Location of Sample	Notes
	(%)	(mm)	(in)	(°C)	(°F)	(°C)	(°F)		
25	-	110	4.25	-	-	17.2	63	-	Sat for 40 min then put in w/o retesting
26		-	-	-	-	16.1	61	-	-
27	9.3	80	3.25	-	-	15.6	60	-	-
28	-	-	-	-	-	16.7	62	-	-
29	-	105	4.25	-	-	17.2	63	-	-
30	-	-	-	-	-	16.7	62	-	Possibly higher slump
31	10.1	100	4	-	-	16.1	61	-	-
32	-	-	-	-	-	16.7	62	-	-
33	-	107	4.25	-	-	15.6	60	-	-
34	-	-	-	-	-	16.1	61	-	-
35	10.5	125	5	-	-	16.1	61	-	On top 9.5% air
36	-	-	-	-	-	15.0	59	-	-
37	-	120	4.75	-	-	16.7	62	-	-
38	-	-	-	-	-	15.6	60	-	-
39	12.5	130	5	-	-	16.7	62	-	Truck rejected for 12.5% air
40	8.4	90	3.5	-	-	16.1	61	-	-
41	-	140	5.5	-	-	15.0	59	-	-
42	-	-	-	-	-	16.1	61	-	-
43	9.6	85	3.25	-	-	15.6	60	-	On top 9% air
44	-	-	-	-	-	16.1	61	-	-
45	-	105	4.25	-	-	15.6	60	-	-
46	-	-	-	-	-	16.1	61	-	-
47	8.5	95	3.75	-	-	16.7	62	-	-
48	-	-	-	-	-	16.1	61	-	-
49	-	95	3.75	-	-	16.7	62	-	-
50	-	-	-	-	-	16.7	62	-	-
51	-	95	3.75	-	-	17.2	63	-	-

Table D.8 (continued) – Individual Plastic Concrete Test Results for LC-HPC and Control Bridge Decks

Truck	Air Content	Slump		Concrete Temperature†		Concrete Surface Temperature††		Location of Sample	Notes
	(%)	(mm)	(in)	(°C)	(°F)	(°C)	(°F)		
52	-	-	-	-	-	17.8	64		$4m^3$ – ½ truck load – may not have used
LC-HPC-7 (43-033) Qualification Slab, Cast on 6/8/2006									
1	9.0	70	2.75	-	-	-	-	-	-
2	8.5	50	2.0	-	-	-	-	-	Cylinders
3	8.0	85	3.25	-	-	-	-	-	-
4	8.5	75	3.0	-	-	-	-	-	-
LC-HPC-7 (43-033) Deck, Cast on 6/24/2006									
-	7.5	70	2.75	-	-	22.8	73	-	-
-	9.0	100	4.0	-	-	23.9	75	-	-
-	8.0	125	5.0	-	-	23.9	75	-	-
-	7.5	135	5.25	-	-	22.8	73	-	-
-	6.5	65	2.5	-	-	22.8	73	-	-
-	-	75	3.0	-	-	23.3	74	-	-
-	6.5	70	2.75	-	-	21.7	71	-	-
-	-	90	3.5	-	-	22.8	73	-	-
-	8.5	90	3.5	-	-	21.7	71	-	-
-	-	65	2.5	-	-	22.2	72	-	-
-	8.5	100	4.0	-	-	22.2	72	-	-
-	-	65	2.5	-	-	20.6	69	-	-
-	8.5	100	4.0	-	-	20.6	69	-	-
-	-	100	4.0	-	-	21.7	71	-	-
-	8.5	150	6.0	-	-	21.1	70	-	-
-	-	65	2.5	-	-	22.8	73	-	-
-	7.0	65	2.5	-	-	22.8	73	-	-
-	-	55	2.25	-	-	20.6	69	-	-
-	9.0	100	4.0	-	-	20.6	69	-	-
-	-	100	4.0	-	-	21.7	71	-	-

Table D.8 (continued) – Individual Plastic Concrete Test Results for LC-HPC and Control Bridge Decks

Truck	Air Content (%)	Slump (mm)	Slump (in)	Concrete Temperature† (°C)	Concrete Temperature† (°F)	Concrete Surface Temperature†† (°C)	Concrete Surface Temperature†† (°F)	Location of Sample	Notes
-	-	100	4.0	-	-	21.1	70	-	-
-	10.5	135	5.25	-	-	20.0	68	-	-
-	7.0	150	6.0	-	-	20.6	69	-	-
Control 7 (46-334) Subdeck Placement 1, Cast on 3/15/2006									
Only average test values were reported									
Control 7 (46-334) SFO Placement 1, Cast on 3/29/2006									
Only average test values were reported									
Control 7 (46-334) Subdeck Placement 2, Cast on 8/16/2006									
Only average test values were reported									
Control 7 (46-334) SFO Placement 2, Cast on 9/15/2006									
Only average test values were reported									
LC-HPC-8 (54-053) Qualification Slab, Cast on 9/26/2007									
1	6.1	25	1	16	61	-	-	Truck	Added 8 gal water back.
1	7.2	60	2.25	16	61	-	-	Truck	Retested. AEA added
1	4.0	35	1.5	18	65	-	-	Deck	Retested
2	9.2	-	-	16	60			Truck	-
2	8.2	55	2.25	19	66	-	-	Deck	-
3	NR	NR	NR	NR	NR	-	-	NR	-
4	8.7	45	1.75	19	66	-	-	Deck	Cylinders
LC-HPC-8 (54-053) Deck, Cast on 10/3/2007									
1	8.1	65	2.5	-	-	-	-	Truck	-
1	7.5	70	2.75	15	59	16.3	61	Deck	-
2	6.9	45	1.75	18	64	-	-	Deck	-
3	-	45	1.75	-	-	-	-	Truck	-
3	5.7	40	1.5	17	63	16.1	61	Deck	-
5	9.0	52	2	16	60	15.8	60	Truck	-
5	7.7	-	-	-	-	-	-	Deck	-
7	-	85	3.25	17	62	16.5	62	Truck	-

Table D.8 (continued) – Individual Plastic Concrete Test Results for LC-HPC and Control Bridge Decks

Truck	Air Content	Slump		Concrete Temperature†		Concrete Surface Temperature††		Location of Sample	Notes
	(%)	(mm)	(in)	(°C)	(°F)	(°C)	(°F)		
7	7.7	55	2.25	16	60	-	-	Deck	-
9	7.3	42	1.5	21	69	17.1	63	Deck	Trip ticket slump = 50mm, air = 6.6%
11	7.7	45	1.75	19	66	18.0	64	Deck	Trip ticket slump = 50mm
13	9.0	42	1.5	18	64	17.6	64	Deck	Trip ticket slump = 56 mm
15	8.2	50	2	21	70	18.6	65	Deck	Trip ticket slump = 55 mm
17	9.0	60	2.25	18	65	17.6	64	Deck	Trip ticket slump = 68 mm
19	8.7	40	1.5	19	66	18.0	64	Deck	Trip ticket slump = 40 mm
21	8.2	43	1.75	21	69	18.6	65	Deck	Trip ticket slump = 40 mm
23	8.2	50	2	22	72	19.8	68	Deck	Trip ticket slump = 75 mm
25	8.7	65	2.5	21	69	18.8	66	Deck	Trip ticket slump = 60 mm
27	7.0	42	1.5	20	68	19.2	67	Deck	Trip ticket slump = 74 mm
29	7.2	40	1.5	21	69	19.4	67	Deck	Trip ticket slump = 40 mm
31	7.2	38	1.5	22	71	19.6	67	Deck	Trip ticket slump = 42 mm
33	7.9	35	1.5	21	69	19.5	67	Deck	Trip ticket slump = 40 mm
35	6.9	55	2.25	22	72	20.8	69	Deck	Trip ticket slump = 62 mm
37	9.8	70	2.75	22	72	21.1	70	Truck	Trip ticket slump = 70 mm
38	8.2	-	-	-	-	-	-	Truck	-
39	-	75	3	22	71	-	-	Deck	-
41	8.8	65	2.5	19	66	-	-	Deck	-
46	6.2	-	-	23	73	-	-	Deck	-
47	-	85	3.25	19	67	-	-	Truck	-
48	8.2	53	2.0	19	67	-	-	Deck	-
50	7.7	70	2.75	20	68	-	-	Deck	-
53	10.2	75	3	18	64	-	-	Deck	-
55	9.7	-	-	-	-	-	-	Deck	-
55	9.7	-	-	-	-	-	-	Deck	-

Table D.8 (continued) – Individual Plastic Concrete Test Results for LC-HPC and Control Bridge Decks

Truck	Air Content	Slump		Concrete Temperature†		Concrete Surface Temperature††		Location of Sample	Notes
	(%)	(mm)	(in)	(°C)	(°F)	(°C)	(°F)		
LC-HPC-10 (54-060) Qualification Slab, Cast on 4/26/2007									
1	8.2	65	2.5	20	68	-	-	-	Held 1 gal/yd^3 at plant. Added 5 gal back and remixed
2	9.2	85	3.25	20	68	-	-	-	Held 1 gal/yd^3 at plant. Added 4 gal back and remixed
3	8.7	68	2.75	21	69	-	-	-	Added SP and remixed
3	-	130	5	-	-	-	-	-	Retested
4	8.8	85	3.25	23	73	-	-	-	-
LC-HPC-10 (54-060) Deck, Cast on 5/17/2007									
1	5.5	70	2.75	17.8	64	-	61	-	Abutment
2	4.9	55	2.25	18.3	65	18.3	65	-	Added AEA and remixed. Abutment
2	5.1	45	1.75	18.3	65	18.1	65	-	Retested. Rejected
3	-	High	-	-	-	15.6	60	-	Rejected
4	7.2	95	3.75	18.5	65	18.5	65	-	Abutment
5	-	85	3.25	18.5	65	18.5	65	-	Abutment
7	6.1	100	4	18.5	65	18.5	65	-	-
9	-	55	2.25	17.5	64	17.5	64	-	-
11	6.5	65	2.5	19.8	68	19.8	68	-	-
15	6.7	70	2.75	18.9	66	18.9	66	-	-
16	-	60	2.25	18.3	65	18.3	65	-	-
17	7.7	90	3.5	18.3	65	18.3	65	-	-
18	6.3	80	3.25	18.3	65	18.3	65	-	-
19	-	75	3	18.3	65	18.3	65	-	-
20	7.7	75	3	18.3	65	18.3	65	-	-
23	-	85	3.25	18.9	66	18.9	66	-	-
25	7.7	80	3.25	18.3	65	18.3	65	-	-
26	-	80	3.25	-	64	-	-	-	-

Table D.8 (continued) – Individual Plastic Concrete Test Results for LC-HPC and Control Bridge Decks

Truck	Air Content	Slump		Concrete Temperature†		Concrete Surface Temperature††		Location of Sample	Notes
	(%)	(mm)	(in)	(°C)	(°F)	(°C)	(°F)		
28	7.7	90	3.5	17.8	65	-	-	-	-
29	-	100	4	15.6	60	18.3	65	-	-
31	7.5	80	3.25	15.6	60		-	-	-
33	-	75	3	18.3	65	18.3	65	-	-
35	9.2	125	5	18.3	65	18.3	65	-	Held back. Lost slump then placed.
37	8.5	85	3.25	18.3	65	18.3	65	-	-
39	-	90	3.5	18.9	66	18.3	65	-	-
42	7.8	75	3	18.9	66	18.9	66	-	-
44	8.2	75	3	19.4	67	19.4	67	-	-
47	7.3	55	2.25	19.4	67	-	-	-	-
50	-	105	4.25	21.1	70	21.1	70	-	-
55	7.7	85	3.25	21.1	70	-	-	-	-
57	-	90	3.5	22.2	72	-	-	-	Placed in deck and abutment
58	-	-	-	-	-	-	-	-	Abutment
59	-	-	-	-	-	22.2	72	-	Abutment
Control 8/10 (54-059) Deck, Cast on 4/16/2007									
1	6.9	125	5	16.7	62	-	-	-	-
6	8.9	135	5.25	20.6	69	-	-	-	-
8	9.5	165	6.5	20.6	69	-	-	-	Cylinders
15	7.5	110	4.25	20.6	69	-	-	-	-
19	7.4	150	6	22.2	72	-	-	-	-
25	6.0	115	4.5	22.8	73	-	-	-	Cylinders
36	7.8	200	7.75	-	-	-	-	-	-
41	7.8	160	6.25	22.2	72	-	-	-	-
45	6.3	100	4	21.1	70	-	-	-	-
50	6.3	105	4.25	23.9	75	-	-	-	-

Table D.8 (continued) – Individual Plastic Concrete Test Results for LC-HPC and Control Bridge Decks

Truck	Air Content (%)	Slump (mm)	Slump (in)	Concrete Temperature† (°C)	Concrete Temperature† (°F)	Concrete Surface Temperature†† (°C)	Concrete Surface Temperature†† (°F)	Location of Sample	Notes
LC-HPC-9 (54-057) Qualification Slab, Attempt 1 on 3/23/2009									
1	7.4	45	1.75	26	78	-	-	Truck	Tested by first crew
1	6.8	40	1.5			-	-	Truck	Tested by second crew
LC-HPC-9 (54-057) Qualification Slab, Attempt 2 on 3/25/2009									
1	9.2	90	3.5	16	60	-	-	Truck	Qualification Batch per request of contractor
LC-HPC-9 (54-057) Qualification Slab, Attempt 3 Cast on 4/1/2009									
1	9.7	100	4	13	55	-	-	Truck	-
1	7.6	75	3	14	58	-	-	Deck	After conveyor, lost 2.1% air and 25 mm (1 in.) slump
2	9.9	117	4.75	14	58	-	-	Deck	Cylinders
3	9.0	-	-	14	58	-	-	Deck	Slump high by visual inspection
LC-HPC-9 (54-057) Deck, Cast on 4/15/2009									
1	6.7	70	2.75	14	58	-	-	Truck	Added AEA (not water) 1 oz/yd3 and remixed
1	5.9	45	1.75	16	60	-	-	Deck	Added the rest of water and remixed
1	6.5	100	4.0	16	60	-	-	Deck	-
2	-	-	-	-	-	-	-		Mixed with Truck 3 at discharge to conveyor belt.
3	8.0	135	5.25	16	60	-	-	Truck	Added all water (at 10:17) before discharge; Wait for slump to drop
3	6.7	80	3.25	16	60	-	-	Deck	Mixed with Truck 2 at discharge to conveyor belt
4	-	-	-	-	-	-	-	-	-
5	7.1	135	5.25	16	60	-	-	Deck	-
6	6.9	100	4.0	16	60	-	-	Truck	AEA at plant 13 oz.

Table D.8 (continued) – Individual Plastic Concrete Test Results for LC-HPC and Control Bridge Decks

Truck	Air Content	Slump		Concrete Temperature†		Concrete Surface Temperature††		Location of Sample	Notes
	(%)	(mm)	(in)	(°C)	(°F)	(°C)	(°F)		
7	-	-	-	-	-	-	-	-	-
8	-	-	-	-	-	-	-	-	-
9	-	75	3.0	16	60	-	-	Deck	-
10	-	-	-	-	-	-	-	-	-
11	-	-	-	17	63	-	-	Truck	If temperature only test, it was taken with standard thermometer, but for the not full time.
12	7.5	90	3.75	18	64	-	-	Deck	Cylinders #50
13	-	-	-	17	63	-	-	Truck	-
14	-	-	-	18	64	-	-	Truck	-
15	-	55	2.25	20	68	-	-	Deck	Out of truck: 6.7%, 50 mm, 65 F
16	-	-	-	18	65	-	-	Truck	-
17	-	-	-	17	63	-	-	Truck	-
18	6.5	75	3.0	17	62	-	-	Deck	Cylinders #51
19	-	-	-	18	65	-	-	Truck	-
20	-	-	-	18	65	-	-	Truck	-
21	5.9	85	3.25	18	64	-	-	Deck	-
22	-	-	-	17	63	-	-	Truck	-
23	-	-	-	18	64	-	-	Truck	-
24	7.1	90	3.5	18	64	-	-	Deck	Cylinders #52
27	6.5	90	3.5	19	66	-	-	Deck	New AEA content
30	7.1	65	2.5	19	66	-	-	Deck	-
33	-	100	4.0	19	66	-	-	Deck	-
36	7.6	75	3.0	20	68	-	-	Deck	-
39	-	100	4.0	21	69	-	-	Deck	-
42	5.7	65	2.5	19	66	-	-	Deck	Cylinders #53
43	6.1	-	-	19	66	-	-	Deck	-
46	6.7	75	3.0	19	66	-	-	Deck	-

Table D.8 (continued) – Individual Plastic Concrete Test Results for LC-HPC and Control Bridge Decks

Truck	Air Content (%)	Slump (mm)	Slump (in)	Concrete Temperature† (°C)	Concrete Temperature† (°F)	Concrete Surface Temperature†† (°C)	Concrete Surface Temperature†† (°F)	Location of Sample	Notes
47	6.1	75	3.0	19	66	-	-	Deck	-
49	-	105	4.0	20	68	-	-	Deck	Cylinders #54
Control 9 (54-058) Subdeck, Cast on 11/3/2007									
1	5.4	50	2	16	61	-	-	-	-
3	6.5	65	2.5	15.5	60	-	-	-	-
12	6.9	70	2.75	16.5	62	-	-	-	Cylinders
18	7.1	75	3	17	63	-	-	-	-
27	6.0	65	2.5	20.5	69	-	-	-	-
32	6.5	55	2.25	21	70	-	-	-	-
41	5.9	95	3.75	22	72	-	-	-	-
44	5.5	60	2.25	22	72	-	-	-	-
Control 9 (54-058) SFO placement 1 (east), Cast on 5/21/2008									
1	5.7	215	8.5	21.5	71	-	-	-	-
7	6.7	170	6.75	21.5	71	-	-	-	Cylinders
Control 9 (54-058) SFO placement 2 (west), Cast on 5/29/2008									
1	5.9	110	4.25	23	73	-	-	-	Cylinders
6	5.2	70	2.75	26.5	80	-	-	-	-
LC-HPC-11 (78-119) Qualification Slab, Cast on 5/25/2007									
1	11	190	7.5	14.5	58	-	-	Truck	Before pump – Rejected
2	9	85	3.25	16.5	62	-	-	Truck	Before pump
2	4.5	70	2.75	19	66	-	-	Deck	After pump
3	6	155	6	19.5	67	-	-	-	-
4	5.2	65	2.5	20	68	-	-	Deck	Cylinders
5	5	60	2.25	19.5	67	-	-	Deck	Cylinders
6	9	-	-	-	-	-	-	Truck	Before pump
6	8	120	4.75	20	68	-	-	Deck	After pump

Table D.8 (continued) – Individual Plastic Concrete Test Results for LC-HPC and Control Bridge Decks

Truck	**Air Content** (%)	**Slump** (mm)	(in)	**Concrete Temperature**† (°C)	(°F)	**Concrete Surface Temperature**†† (°C)	(°F)	**Location of Sample**	**Notes**
LC-HPC-11 (78-119) Deck, Cast on 6/9/2007									
1	7	55	2.25	16	59.7	15.6	60	Truck	4 yard load, placed directly out of chute
2	7.6	73	2.75	15	58.5	15	59	-	Placed out of chute again, 5 cylinders cast
3	6	60	2.25	16	60	15.6	60	-	Allowed despite low air, as most was placed in abutment (chute again)
4	5.4	45	1.75	16	61.3	16.1	61	-	Water added to improve original low slump, rejected for low air
5	6.8	70	2.75	15	58.9	15	59	-	Conveyor used to place on deck
7	7	100	4	15	59	15	59	-	Conveyor used to place on deck
9	7.8	75	3	16	60.8	16.1	61	-	Allowed to continue turning in truck to improve slump
11	8.6	140	5.5	15	59.7	15.6	60	-	Allowed to continue turning in truck to improve slump
11	-	120	4.75	-	-	-	-	-	Continued turning in truck to improve slump (truck #12 poured in the meantime)
11	-	100	4	-	-	-	-	-	5 more cylinders cast
13	8.5	62	2.5	16	59.9	15.6	60	-	Temperature was taken in small amount of concrete leftover after other tests done
15	7.8	60	2.5	17	62.7	17.2	63	-	-
17	8.4	94	3.75	16	60	16.1	60	-	-
19	9	100	4	16	59.8	16.1	60	-	Results of testing done right out of truck chute

Table D.8 (continued) – Individual Plastic Concrete Test Results for LC-HPC and Control Bridge Decks

Truck	Air Content (%)	Slump (mm)	Slump (in)	Concrete Temperature† (°C)	Concrete Temperature† (°F)	Concrete Surface Temperature†† (°C)	Concrete Surface Temperature†† (°F)	Location of Sample	Notes
19	6.6	-	-	-	-	-	-	-	Results of testing done on concrete out of the conveyor hose
21	9.2	100	4	17	62.4	17.2	63	-	-
23	-	80	3.25	18	64.4	17.8	64	-	Problem getting good seal for air content test
23	7.5	-	-	-	-	-	-	-	Concrete from bottom of wheelbarrow after sitting for about 25 minutes
Control 11 (56-155) North ½ Subdeck, Cast on 2/3/2006									
-	5.5	60	2.25	-	-	-	-	-	-
-	6.5	110	4.25	-	-	-	-	-	-
-	6.8	60	2.25	-	-	-	-	-	-
-	7.3	110	4.25	-	-	-	-	-	-
-	7.5	120	4.75	-	-	-	-	-	-
-	7.0	70	2.75	-	-	-	-	-	-
Control 11 (56-115) South ½ Subdeck, Cast on 2/14/2006									
-	6.0	65	2.5	-	-	-	-	-	-
-	7.9	130	5	-	-	-	-	-	-
-	7.2	105	4.25	-	-	-	-	-	-
-	6.9	110	4.25	-	-	-	-	-	-
-	8.0	160	6.25	-	-	-	-	-	-
-	7.0	180	7	-	-	-	-	-	-
-	8.0	210	8.25	-	-	-	-	-	-
-	7.5	100	4	-	-	-	-	-	-
Control 11 (56-115) SFO, Cast on 3/28/2006									
-	5.0	65	2.5	-	-	-	-	-	-
-	7.0	90	3.5	-	-	-	-	-	-

Table D.8 (continued) – Individual Plastic Concrete Test Results for LC-HPC and Control Bridge Decks

Truck	Air Content	Slump		Concrete Temperature†		Concrete Surface Temperature††		Location of Sample	Notes
	(%)	(mm)	(in)	(°C)	(°F)	(°C)	(°F)		
LC-HPC-12 (56-057 Unit 2) Qualification Slab, Cast on 3/28/2008									
1	7.6	108	4.25	13	56	-	-	-	Air temp 3°C (38°F)
1	-	95	3.75	-	-	-	-	-	Retest
1	8.5	95	3.75	15	59	-	-	-	Retest taken from middle of truck. Air temp 4°C (39°F)
2	8.4	133	5.25	14	57	-	-	-	-
2	-	125	5	-	-	-	-	-	10 minutes later
2	7.5	114	4.5	14	57	-	-	-	Taken from middle of truck
3	-	150	6	-	-	-	-	-	Rejected
4	7.6	70	2.75	13	56	-	-	-	Cylinders, Air temp 4°C (39°F)
5	8	83	3.25	13	56	-	-	-	Taken from slab. Air temp 4°C (39°F)
5	8	95	3.75	14	57	-	-	-	Retest. Air temp 4°C (39°F)
LC-HPC-12 (56-057 Unit 2) Phase 1, Cast on 4/4/2008									
1	6.1	40	1.5	14	58	13.3	56	-	Initially a 0.42 *w/c* ratio
1	6.2	45	1.75	15	59	-	-	-	Water added to bring up to 0.44 *w/c* ratio
2	5.7	40	1.5	15	59	13.9	57	-	-
2	6.8	45	1.75	-	-	-	-	-	MRWR added and retested
3	8.1	85	3.25	-	-	13.1	56	Deck	-
4	7.3	70	2.75	-	-	13.6	56	Deck	-
5	-	-	-	-	-	13.6	57	-	-
6	7.9	65	2.5	-	-	12.3	54	Deck	-
7	-	-	-	-	-	13.8	57	-	-
8	-	65	2.5	-	-	13.9	57	-	-
9	7.2	70	2.75	16	60	11.9	53	Deck	-
10	-	85	3.25	-	-	14.1	57	Deck	-
11	-	85	3.25	-	-	13.9	57	Deck	-

Table D.8 (continued) – Individual Plastic Concrete Test Results for LC-HPC and Control Bridge Decks

Truck	Air Content	Slump		Concrete Temperature†		Concrete Surface Temperature††		Location of Sample	Notes
	(%)	(mm)	(in)	(°C)	(°F)	(°C)	(°F)		
12	-	-	-	-	-	14.1	57	-	-
13	7.6	75	3.0	-	-	14.6	58	Deck	-
14	-	-	-	-	-	14.7	59	-	-
15	-	70	2.75	16	61	13.8	57	Deck	-
16	7.9	85	3.25	-	-	15.4	60	Deck	-
17	-	-	-	-	-	14.2	58	-	-
18	-	-	-	-	-	14.5	58	-	-
19	-	70	2.75	-	-	14.7	58	Deck	-
20	-	-	-	-	-	14.4	58	-	-
21	8.0	90	3.5	-	-	14.9	59	Deck	-
22	-	-	-	-	-	14.8	59	-	-
23	-	75	3.0	-	-	16.0	61	Deck	-
24	-	-	-	-	-	16.0	61	-	-
25	7.4	70	2.75	17	62	15.6	60	Deck	-
26	-	-	-	-	-	15.9	61	-	-
27	-	-	-	-	-	19.6	67	-	-
28	-	-	-	-	-	16.0	61	-	-
LC-HPC-12 (56-057 Unit 2) Phase 2, Cast on 3/18/2009									
1	5.3	70	2.75*	21	71	-	-	Truck	0.45 *w/c*. Rejected.
2	7.0	108	4.25	21	70	18	65	Truck	-
3	5.7	89	3.5	20	69	18	65	Truck	-
3	8.4	-	-	-	-	-	-		Redosed with AEA
4	9.0	146	5.75*	19	66	-	-	Truck	Truck set aside. Wait for slump to drop. Not retested.
5	-	-	-	-	-	-	-	-	-
6	-	140	5.5	16	61	16	61	Truck	Placed in deck. Test next truck.
7	7.9	89	3.5	21	69	-	-	Truck	5 cylinders
8	8.9	100	4.0	21	69	-	-	Truck	New mix design 0.44 *w/c*

Table D.8 (continued) – Individual Plastic Concrete Test Results for LC-HPC and Control Bridge Decks

Truck	Air Content (%)	Slump (mm)	Slump (in)	Concrete Temperature† (°C)	Concrete Temperature† (°F)	Concrete Surface Temperature†† (°C)	Concrete Surface Temperature†† (°F)	Location of Sample	Notes
9	-	-	-	-	-	-	-	-	-
10	-	-	-	-	-	-	-	-	-
11	7.7	89	3.5	22	71	18	64	Deck	-
12	-	-	-	-	-	-	-	-	Back to 0.45 *w/c* mix design
13	-	121	4.75	22	71	19	66	Deck	-
14	-	-	-	-	-	-	-	-	-
15	6.3	89	3.5	22	72	18	64	Deck	-
16	5.8*	-		-	-	-	-	Truck	-
16	8.4	-		-	-	-	-	Truck	-
17	7.8	-	-	-	-	-	-	-	Test by concrete supplier
18	7.4	89	3.5	21	71	-	-	Deck	5 cylinders
19	-	-	-	-	-	-	-	-	-
20	-	125	5	18	64	-	-	Deck	-
21	-	-	-	-	-	-	-	-	-
22	-	-	-	-	-	-	-	-	Back to 0.44 *w/c* mix design and cut heated water to reduce ER
23	7.9	89	3.5	17	63	-	-	Deck	Back to 0.44 *w/c* mix design
24	-	-	-	-	-	-	-	-	-
25	-	133	5.25	-	-	-	-	Truck	Placed in deck. Test next truck
26	-	159	6.25*	-	-	-	-	Truck	Placed in N abutment
27	6.6	89	3.5	17	62	-	-	Truck	Last truck to finish deck
28	-	-	-	-	-	-	-	-	Placed in N abutment
29	-	-	-	-	-	-	-	-	Backordered 7 yd^3, placed in wing wall.
Control 12 (56-057 Unit 1) Phase 1 Subdeck, Cast on 3/11/2008									
-	6.3	83	3.25	24	75	-	-	-	Cylinders
-	6.4	140	5.5	24	76	-	-	-	-
-	7.1	89	3.5	22	71	-	-	-	Cylinders

Table D.8 (continued) – Individual Plastic Concrete Test Results for LC-HPC and Control Bridge Decks

Truck	Air Content	Slump		Concrete Temperature†		Concrete Surface Temperature††		Location of Sample	Notes
	(%)	(mm)	(in)	(°C)	(°F)	(°C)	(°F)		
-	7.6	127	5.0	22	72	-	-	-	-
Control 12 (56-057 Unit 1) Phase 1 SFO, Cast on 4/1/2008									
	2.7	64	2.5	17	62	-	-	-	Test completed as truck unloaded
	2.5	114	4.5	17	62	-	-	-	Used to avoid construction joint
	8.2	114	4.5	17	62	-	-	-	Added 6 oz AEA on jobsite, Cylinders
	9.9	64	2.5	10	50	-	-	-	Added 6 oz AEA on jobsite, cylinders
	9.1	114	4.5	17	62	-	-	-	Cylinders
	7.9	89	3.5	11	51	-	-	-	-
	7.4	89	3.5	16	61	-	-	-	-
Control 12 (56-057 Unit 1) Phase 2 Subdeck, Cast on 3/13/2009									
-	7.6	95	3.75	21	69	-	-	-	Air Temperature 38°F
-	8.0	95	3.75	22	72	-	-	-	Air Temperature 54°F
-	6.0	140	5.5	23	74	-	-	-	Air Temperature 47°F
-	7.3	115	4.5	22	72	-	-	-	Air Temperature 42°F
-	7.2	145	5.75	22	71	-	-	-	Air Temperature 41°F
Control 12 (56-057 Unit 1) Phase 2 SFO, Cast on 4/14/2009									
1	6.9	70	2.75	17	62	-	-	-	-
2	8.5	45	1.75	17	62	-	-	-	-
LC-HPC-13 (54-066) Qualification Slab, Cast on 4/16/2008									
1	5.7	70	2.75	23	73.6	-	-	Truck	Sample from first portion of the truck
1	6.0	100	4.0	24	75.3	-	-	Deck	Sample from middle of truck
2		-	-	-	-	-	-	-	-
3	5.4	110	4.25	21	70.1	-	-	Truck	Sample from middle of truck
3	6.25	115	4.5	23	73.5	-	-	Deck	Sample from middle of truck
4	7.0	100	4.0	20	68.4	-	-	Truck	Sample from middle of truck

Table D.8 (continued) – Individual Plastic Concrete Test Results for LC-HPC and Control Bridge Decks

Truck	Air Content	Slump		Concrete Temperature†		Concrete Surface Temperature††		Location of Sample	Notes
	(%)	(mm)	(in)	(°C)	(°F)	(°C)	(°F)		
4	6.5	100	4.0	22	71.0	-	-	Pump	Sample from middle of truck
5	-	-	-	-	-	-	-	-	-
6	6.0	135	5.25	21	70.4	-	-	Pump	Sample from middle of truck
LC-HPC-13 (54-066) Deck, Cast on 4/29/2008									
1	8.3	75	3	16	61	-	-	Truck	-
1	7.5	85	3.25	-	-	-	-	Deck	Added 0.5 oz/yd^3 AEA
2	11.0	100	4	17	62	-	-	Truck	Added 0.5 oz/yd^3 AEA
2	9.0	75	3	-	-	-	-	Deck	-
3	10.0	100	4	17	62	-	-	Truck	-
3	9.5	75	3	-	-	-	-	Deck	-
4	-	-	-	-	-	-	-	-	-
5	-	55	2.25	20	68	-	-	Deck	-
8	6.8	50	2	21	70	-	-	Deck	Cylinders
9	-	75	3	-	-	-	-	Deck	-
12	7.0	75	3	20	68	-	-	Deck	-
14	7.3	95	3.75	21	70	-	-	Deck	-
16	-	65	2.5	22	71	-	-	Deck	Added 0.5 oz/yd^3 AEA
18	8.0	100	4	22	71	-	-	Deck	Added 0.5 oz/yd^3 AEA
20	-	100	4	21	70	-	-	Deck	-
22	6.8	45	1.75	22	71	-	-	Deck	-
24	-	65	2.5	22	72	-	-	Deck	-
26	7.0	65	2.5	21	70	-	-	Deck	-
28	-	50	2	22	71	-	-	Deck	-
30	7.7	75	3	21	70	-	-	Deck	-
32	-	65	2.5	21	70	-	-	Deck	-
34	8.7	70	2.75	21	70	-	-	Deck	-
36	-	100	4	21	69	-	-	Deck	Slump measured from lowest portion of concrete

Table D.8 (continued) – Individual Plastic Concrete Test Results for LC-HPC and Control Bridge Decks

Truck	Air Content (%)	Slump (mm)	Slump (in)	Concrete Temperature† (°C)	Concrete Temperature† (°F)	Concrete Surface Temperature†† (°C)	Concrete Surface Temperature†† (°F)	Location of Sample	Notes
38	9.2	110	4.25	21	69	-	-	Deck	Air reading high, then dropped
40	-	100	4	21	70	-	-	Deck	-
42	9.2	75	3	21	69	-	-	Deck	-
44	-	125	5	21	69	-	-	Deck	Appeared to have high slump
45	-	70	2.75	-	-	-	-	Truck	-
46	8.7	75	3	21	70	-	-	Deck	-
48	-	75	3	21	69	-	-	Deck	-
50	9.2	95	3.75	21	69	-	-	Deck	-
52	-	70	2.75	20	68	-	-	Deck	-
54	7.9	70	2.75	19	67	-	-	Deck	-
56	-	45	1.75	21	69	-	-	Deck	Removed 0.5 gal/yd^3
58	7.5	55	2.25	22	72	-	-	Deck	-
60	-	70	2.75	21	70	-	-	Deck	-
Control 13 (54-067) Subdeck, Cast on 7/11/2008									
-	7.2	60	2.25	31	87	-	-	-	-
-	6.1	95	3.75	33	91	-	-	-	-
-	5.0	68	2.75	32	89	-	-	-	-
-	5.4	115	4.5	32	89	-	-	-	-
-	5.0	75	3.0	31	87	-	-	-	-
-	5.9	130	5.0	32	89	-	-	-	No cylinders
Control 13 (54-067) SFO, Cast on 7/25/2008									
-	6.5	97	3.75	33	91	-	-	-	Cylinders
-	6.1	168	6.75	33	91	-	-	-	-
LC-HPC-14 (46-363) Qualification Slab, Cast on 11/13/2007									
1	8.5	66	2.5	21	70	-	-		Air Temp=67°F
2	8.0	83	3.25	21	70	-	-		Air Temp=69°F
3	6.6	83	3.25	20.5	69	-	-		Air Temp=65°F
4	-	-	-	-	-	-	-		-

Table D.8 (continued) – Individual Plastic Concrete Test Results for LC-HPC and Control Bridge Decks

Truck	Air Content	Slump		Concrete Temperature†		Concrete Surface Temperature††		Location of Sample	Notes
	(%)	(mm)	(in)	(°C)	(°F)	(°C)	(°F)		
5	7.6	70	2.75	20	68	-	-	-	-
6	7.4	77	3	21	70	-	-	-	-
LC-HPC-14 (46-363) Deck phase 1 placement 1 – Attempt 2, Cast on 12/19/2007									
-	8.8	64	2.5	18.5	65	18.5	65	-	-
-	7.9	44	1.75	18	64	18	64	-	6 cylinder
-	-	51	2	19	66	19	66	-	-
-	7.8	102	4	20.5	69	20.5	69	-	1 ½ buckets of water added, 6 cylinders
-	7.	95	3.75	18.5	65	18.5	65	-	6 cylinders
-	9.0	89	3.5	18.5	65	18.5	65	-	6 cylinders
-	9.1	113	5.25	19	66	19	66	-	6 cylinders
-	8.7	146	5.75	19.5	67	19.5	67	-	6 cylinders
-	-	102	4	-	-	-	-	-	-
-	-	127	5	-	-	-	-	-	-
-	9.0	95	3.75	17	63	17	63	-	-
-	9.1	102	4	15.5	60	15.5	60	-	6 cylinders
-	4.7	108	4.25	18.5	65	18.5	62	-	6 cylinders
LC-HPC-14 (46-363) Deck phase 2 – Placement 2, Cast on 5/2/2008									
1	11	108	4.25	18.5	65	18.5	65	-	-
2	10.4	127	5	17	63	17	63	-	-
3	10.9	152	6	18	64	18	64	-	-
4	8.1	133	5.25	18	64	18	64	-	-
4-Deck	6.7	114	4.5	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-	-
8	12	102	4	18.5	65	18.5	65	-	-
8R	10.7	-	-	-	-	-	-	-	-

Table D.8 (continued) – Individual Plastic Concrete Test Results for LC-HPC and Control Bridge Decks

Truck	Air Content	Slump		Concrete Temperature†		Concrete Surface Temperature††		Location of Sample	Notes
	(%)	(mm)	(in)	(°C)	(°F)	(°C)	(°F)		
9	-	-	-	-	-	-	-	-	-
10	-	-	-	-	-	-	-	-	-
11	-	-	-	-	-	-	-	-	-
12	-	-	-	-	-	-	-	-	-
13	10.5	108	4.25	18	64	18	64	-	-
14	-	-	-	-	-	-	-	-	-
15	-	-	-	-	-	-	-	-	-
16	10.4	89	3.5	-	-	-	-	-	-
17	10.5	102	4	18.5	65	18.5	65	-	-
18	-	-	-	-	-	-	-	-	-
19	-	-	-	-	-	-	-	-	-
20	-	-	-	-	-	-	-	-	-
21	-	-	-	-	-	-	-	-	-
22	10.4	114	4.5	18.5	65	18.5	65	-	-
22-Deck	8.0	102	4	-	-	-	-	-	-
23	-	-	-	-	-	-	-	-	-
24	-	-	-	-	-	-	-	-	-
25	-	-	-	-	-	-	-	-	-
26	-	-	-	-	-	-	-	-	-
27	-	-	-	-	-	-	-	-	-
28	7.0	64	2.5	18	64	18	64	-	-
29	-	-	-	-	-	-	-	-	-
30	-	-	-	-	-	-	-	-	-
31	8.1	89	3.5	18	64	18	64	-	-
32	-	-	-	-	-	-	-	-	-
33	-	-	-	-	-	-	-	-	-
34	-	-	-	-	-	-	-	-	6 cylinders
35	-	-	-	-	-	-	-	-	5 cylinders

Table D.8 (continued) – Individual Plastic Concrete Test Results for LC-HPC and Control Bridge Decks

Truck	Air Content	Slump		Concrete Temperature†		Concrete Surface Temperature††		Location of Sample	Notes
	(%)	(mm)	(in)	(°C)	(°F)	(°C)	(°F)		
LC-HPC-14 (46-363) Deck phase 2 – Placement 3, Cast on 5/21/2008									
-	10.5	135	5.25	19.5	67	19.5	67	Truck	Air Temp = 77° F, north abdument
-	10.5	165	6.5	18.5	65	18.5	65	Truck	Air Temp = 76° F, north abdument
-	9.9	150	6	17.5	63.5	17.5	63.5	Truck	Air Temp = 76° F, north abdument
-	9.5	115	4.5	16.5	62	16.5	62	Truck	Air Temp = 74° F, deck
-	9	50	2	19	66	19	66	Deck	Deck
-	8	85	3.25	19.5	67	19.5	67	Truck	Add 10 gal w back
-	9.6	130	5	19.5	67	19.5	67	Truck	deck
-	9.8	130	5	19	66	19	66	Truck	-
-	8.6	75	3	19	66	19	66	Deck	-
-	9.5	110	4.25	17	63	17	63	Truck	-
ALT Control (56-049), Cast on 6/2/2005									
-	5.6	76	3	-	-	-	-	-	-
-	6.9	70	2.75	-	-	-	-	-	-
-	7.3	70	2.75	-	-	-	-	-	-
-	7.0	76	3	-	-	-	-	-	-

† ASTM C1064

†† Infrared measurement of concrete surface temperature.

Table D.9 – Individual Burlap Placement Times for LC-HPC Bridge Decks

Location	Time					Notes
	Place Concrete in Forms	Strike Off	Place Burlap First Layer	Place Burlap Second Layer	Time to Burlap (min.)	
LC-HPC-1 (105-304) Qualification Slab, Cast on 9/8/2005						
0 ft	-	9:00	9:37	-	37	-
15	-	9:39	10:13	-	34	Finishing stopped at 9:42, started at 10:02
22	-	10:07	10:16	-	9	-
30	-	10:14	10:18	-	4	-
LC-HPC-1 (105-304) Placement 1, Cast on 10/14/2005						
East Abutment	-	7:05	7:26	7:30	21	7:14 Bullfloating is working fogging water into the surface
2	-	7:23	7:34	7:36	11	-
4	-	7:30	7:45	-	15	-
6	-	7:42	7:58	7:59	16	-
8	7:46	7:55	8:06	8:07	11	7:46 Hose used to wet down burlap that was dry in spots at approximately brace 5
10 A	7:56	8:05	8:25		20	7:59 Water starts flowing through one of the soaker hoses
10 B	7:56	8:13	8:26		13	8:03 Brace 7 burlap dry in spots
12	8:11	8:23	8:40	8:40	17	-
14	8:25	8:35	8:50	8:50	15	-
16	-	8:44	8:55	8:55	11	8:55 Paused while filling abutment
18	-	8:53	9:22	9:22	29	-
End	-	9:11	9:31	9:31	14	-

Table D.9 – Individual Burlap Placement Times for LC-HPC Bridge Decks

Location	Time					Notes
	Place Concrete in Forms	Strike Off	Place Burlap First Layer	Place Burlap Second Layer	Time to Burlap (min.)	
LC-HPC-1 (105-304) Placement 2, Cast on 11/2/2005						
East Abutment	7:37	7:51	8:08	8:10	17	-
20 ft	8:00	8:13	8:23		10	-
40	8:17	8:25	8:32		15	-
60	8:29	8:37	8:48		11	-
80	8:47	8:54	9:04	9:04	10	-
100	9:00	9:07	9:15	9:15	8	-
120	9:20	9:26	9:34	9:34	8	-
140	9:35	9:59	10:13	10:13	14	Operation paused for 4 min.
150 West Abutment	-	10:05	10:16	-	11	-
LC-HPC-2 (105-310), Cast on 9/13/2006						
0 – East Abutment	-	-	-	-	-	Operation paused from 6:28 to 6:32 (8 min.)
5	-	6:32	6:43	-	11	Operation paused 11 min. due to no concrete
9	-	7:05	7:20	-	15	-
11	-	7:23	7:37	-	14	Operation paused for 17 minutes
13	-	7:43	7:53	-	10	-
15	-	8:12	8:37	-	25	Operation paused for 17 minutes
17	-	8:41	9:09	-	28	-
19	-	9:06	9:22	-	16	-
19 – West Abutment	-	9:14	9:26	-	12	-

Table D.9 – Individual Burlap Placement Times for LC-HPC Bridge Decks

Location	Time					Notes
	Place Concrete in Forms	Strike Off	Place Burlap First Layer	Place Burlap Second Layer	Time to Burlap (min.)	
LC-HPC-3,4,5 and 6 (46-338, 46-339, 46-340, and 46-340 Units 1 and 2) Qualification Slab, Cast on 9/14/2007						
5 ft	7:20	7:35	8:11	-	36	-
10	7:40	8:05	8:37	-	32	-
15	8:15	8:35	8:46	-	11	-
20	8:30	8:40	8:53	-	13	-
LC-HPC-3 (46-338) Deck, Cast on 11/13/2007						
1 (10 ft intervals)	2:45 a.m.	3:00	3:16	-	16	Start pouring at 2:35, from east to west
2	2:55	3:05	3:26	-	21	Bullfloating was used
3	3:10			-		-
4		3:25	3:36	-	11	-
5	3:19			-		Before this point, water was used to help finish the side and was stopped immediately
7		3:43	3:57	-	14	-
8	3:48	3:55	4:06	-	11	-
9	3:56	4:04	4:19	-	15	-
10	4:15	4:15	4:28	-	13	-
11	-	-	-	-	-	4:45 a.m., began placing burlap on side
16	5:13	5:19	5:33	-	14	5:36-5:40 Delay in concrete delivery
17	5:19	5:31	5:48	-	17	-
18	5:30	5:49	6:03	-	14	-
23	6:30	6:41	6:57	-	16	-

Table D.9 – Individual Burlap Placement Times for LC-HPC Bridge Decks

Location	Time					Notes
	Place Concrete in Forms	Strike Off	Place Burlap First Layer	Place Burlap Second Layer	Time to Burlap (min.)	
24	6:40	6:48	7:08	-	20	Workers left burlap placement to set up hoses
25	6:30	7:05	7:14	-	9	-
28	7:15	7:23	7:48	-	25	-
30	7:43	7:51	8:02	-	11	7:28-7:38 Delay in concrete (failed slump test)
34	-	8:25	8:38	-	13	-
35	8:25	8:35	8:45	-	10	-
36	8:33	8:41	8:55	-	14	-
37	-	8:47	9:06	-	19	-
38	8:46	8:54	9:13	-	19	-
39	-	9:05	9:18	-	13	-
40	-	9:13	9:27	-	14	No delay at the abutment. The burlap on the side was finished at 9:43 a.m.
LC-HPC-4 (46-339) Deck stopped at header, Cast on 9/29/2007						
Start	1:47	1:50	-	-	-	-
	2:10	2:30	2:44 to 2:49	-	-	1:55-2:05 Delay due to pumping
3	-	2:35	-	-	-	-
3-5	Refinished	3:15	3:19 to 3:24	-	-	Delay due to out of spec concrete
8	3:05	3:30	3:40	-	10	-
11	3:30	3:41	3:51	-	10	-
14	-	4:12	4:40	-	8	3:45 Delay due to pumping
15	-	-	4:44	-	-	-

Table D.9 – Individual Burlap Placement Times for LC-HPC Bridge Decks

Location	Time					Notes
	Place Concrete in Forms	Strike Off	Place Burlap First Layer	Place Burlap Second Layer	Time to Burlap (min.)	
16	-	-	4:48	-	-	Some uncovered concrete sprayed with water
17	-	5:04	5:11	-	7	Some uncovered concrete sprayed with water
18	-	5:05	5:13	-	8	Some water may have been worked into surface
19	4:10	-	5:16	-	-	-
20	4:53	5:11	5:18	-	7	-
21	-	5:14	5:22	-	8	-
22	-	5:17	5:25	-	8	-
23	-	5:20	5:33	-	13	-
24	5:12	5:22	5:40	-	8	-
25	5:15	5:32	5:42	-	10	5:25 Delay on finish due to equipment spacing
26	5:18	5:39	5:51	-	12	Delay at 5:35
27	5:21	5:42	5:54	-	12	Delay for more burlap (crane)
End	5:23	-	-	-	-	Consolidate at 5:26
LC-HPC-4 (46-339) Deck completed, Cast on 10/2/2007						
1	1:33	1:43	1:53	-	10	Work bridges were set on the deck that was finished two days prior
2	1:40	1:48	2:01	-	13	-
3	1:47	1:55	2:08	-	13	-
4	-	2:04	2:17	-	13	-
5	2:03	2:14	2:24	-	10	2:08-2:10 wait for concrete
8	-	2:29	2:48	-	19	Finished the curb on the edge

Table D.9 – Individual Burlap Placement Times for LC-HPC Bridge Decks

Location	Time					Notes
	Place Concrete in Forms	Strike Off	Place Burlap First Layer	Place Burlap Second Layer	Time to Burlap (min.)	
9	2:25	2:34	2:52	-	18	-
10	2:31	-	2:56	-	-	-
12	-	2:48	3:06	-	18	-
13	2:46	-	-	-	0	-
15	-	3:07	3:22	-	15	-
16	-	3:13	3:26	-	13	-
17	3:07	3:21	3:31	-	10	-
18	3:14	3:23	3:36	-	13	-
19	-	3:30	3:43	-	13	-
20	3:25	3:37	3:47	-	10	-
21	3:32	3:43	3:50	-	7	-
23	-	3:48	4:02	-	14	-
24	3:46	3:54	4:07	-	13	-
25	3:48	4:04	4:13	-	9	-
26	3:59	4:07	4:19	-	12	-
28	4:09	4:17	4:30	-	13	-
33	-	4:44	5:27	-	43	4:51-5:09 Wait for concrete. Disassemble work bridge.
34	4:33	5:11	5:50	-	39	-
35 (north end)	5:12	5:22	5:54	-	32	-
LC-HPC-5 (46-340 Unit 1), Cast on 11/14/2007						
Strut 1	3:00	3:21	3:35	-	14	-
3	-	-	-	-	8	-
5	-	-	-	-	11	-
7	-	-	-	-	9	-

Table D.9 – Individual Burlap Placement Times for LC-HPC Bridge Decks

Location	Time					Notes
	Place Concrete in Forms	Strike Off	Place Burlap First Layer	Place Burlap Second Layer	Time to Burlap (min.)	
9	-	-	-	-	13	4:15 Watering the burlap
11	-	-	-	-	-	-
13	-	-	-	-	14	-
15	-	-	-	-	11	-
17	-	-	-	-	15	-
19	-	-	-	-	-	-
21	-	-	-	-	-	-
23	-	-	-	-	-	-
25	-	-	-	-	13	-
27	-	-	-	-	14	-
29	-	-	-	-	12	-
31	-	-	-	-	14	-
33	-	-	-	-	14	-
35	-	-	-	-	11	-
37	-	-	-	-	12	-
39	-	-	-	-	11	-
41	-	-	-	-	11	-
43	-	-	-	-	7	-
45	-	-	-	-	11	-
47	-	-	-	-	8	-
49	-	-	-	-	11	-
51	-	-	-	-	8	-
53	-	-	-	-	-	-
55	-	-	-	-	-	-
57	-	-	-	-	-	-
59	-	-	-	-	12	-

Table D.9 – Individual Burlap Placement Times for LC-HPC Bridge Decks

Location	Time					Notes
	Place Concrete in Forms	Strike Off	Place Burlap First Layer	Place Burlap Second Layer	Time to Burlap (min.)	
61	-	-	-	-	15	Delay due to concrete
63	-	-	-	-	8	-
65	-	-	-	-	15	Delay due to concrete
67	-	-	-	-	15	-
69	-	-	-	-	14	-
71	-	-	-	-	10	-
73	-	-	-	-	13	-
75	-	-	-	-	16	-
77	-	-	-	-	22	-
79	-	-	-	-	5	-
81	-	-	-	-	-	Many strips of burlap were not fully saturated when laid down but were rewet thoroughly immediately after placement
LC-HPC-6 (46-340 Unit 2), Cast on 11/3/2007						
Support 1	5:40	5:55	6:05	-	10	-
2	5:50	6:03	6:08	-	5	-
3	-	6:05	6:10	-	5	-
4	-	6:08	6:12	-	4	-
5	-	6:11	6:15	-	4	-
6	-	6:14	6:20	-	6	-
7	-	6:19	6:32	-	13	5 min. delay due to concrete
8	-	6:27	6:32	-	5	-
9	-	6:32	6:35	-	3	-
10	-	6:35	6:39	-	4	-
11	-	6:38	6:41	-	3	-

Table D.9 – Individual Burlap Placement Times for LC-HPC Bridge Decks

Location	Time					Notes
	Place Concrete in Forms	Strike Off	Place Burlap First Layer	Place Burlap Second Layer	Time to Burlap (min.)	
12	-	6:40	6:47	-	7	-
13	-	6:42	6:49	-	7	-
14	-	6:48	7:00	-	12	5 min. delay due to concrete
15	-	6:58	7:06	-	8	-
16	-	7:02	7:09	-	7	-
17	-	7:07	7:12	-	5	-
18	-	7:11	7:19	-	8	-
19	-	7:15	7:21	-	6	-
20	-	7:19	7:23	-	4	-
21	-	7:22	7:24	-	2	-
22	-	7:26	7:46	-	20	Delay
23	-	7:29	7:48	-	19	-
24	-	7:38	7:50	-	12	-
25	-	7:41	7:52	-	11	-
26	7:28	7:44	7:54	-	10	-
27	-	7:47	7:56	-	9	-
28	-	7:53	8:02	-	6	-
29	-	7:57	8:06	-	5	-
30	-	8:00	8:16	-	6	-
31	-	8:03	8:18	-	13	Delay due to waiting for more burlap
32	-	8:06	8:19	-	12	-
33	-	8:09	8:20	-	10	-
34	-	8:12	8:21	-	8	-
35	-	8:15	8:22	-	6	-
36	-	8:17	8:24	-	5	-

Table D.9 – Individual Burlap Placement Times for LC-HPC Bridge Decks

Location	Time					Notes
	Place Concrete in Forms	Strike Off	Place Burlap First Layer	Place Burlap Second Layer	Time to Burlap (min.)	
37	-	8:19	8:39	-	5	-
38	-	8:22	8:40	-	17	Some fogging performed
39	-	8:36	8:43	-	4	Small amount of water was worked into the surface
40	-	8:40	8:46	-	3	-
41	-	8:43	8:46	-	3	-
42	-	8:46	8:49	-	3	-
43	-	8:49	8:52	-	3	-
44	-	8:52	8:55	-	3	-
45	-	8:54	8:56	-	2	-
46	-	8:57	9:02	-	5	-
47	-	9:01	9:04	-	3	-
48	-	9:03	9:10	-	7	-
49	-	9:07	9:11	-	4	-
50	-	9:10	9:15	-	5	-
51	-	9:14	9:16	-	2	-
52	-	9:16	9:25	-	9	Short delay due to concrete
53	-	9:25	9:30	-	5	-
54	-	9:28	9:33	-	5	-
55	-	9:32	9:36	-	4	-
56	-	9:35	9:37	-	2	-
57	-	9:37	9:42	-	5	-
58	-	9:42	9:46	-	4	-
59	-	9:45	9:49	-	4	-
60	-	9:47	9:50	-	3	-
61	-	9:50	9:59	-	9	-

Table D.9 – Individual Burlap Placement Times for LC-HPC Bridge Decks

Location	Time					Notes
	Place Concrete in Forms	Strike Off	Place Burlap First Layer	Place Burlap Second Layer	Time to Burlap (min.)	
62	-	9:57	10:00	-	3	-
63	-	10:00	10:05	-	5	-
64	-	10:03	10:13	-	10	-
65	-	10:07	10:15	-	8	-
66	-	10:12	10:17	-	5	-
67	-	10:16	10:22	-	6	-
68	-	10:22	10:26	-	4	-
69	-	10:25	10:29	-	4	-
70	-	10:29	10:36	-	7	-
71	-	10:34	10:41	-	7	-
72	-	10:36	10:55	-	19	Delay due to pump change
73	-	10:40	10:56	-	16	-
74	-	10:55	11:06	-	11	Pumping stopped frequently for short periods of time
75	-	11:05	11:15	-	10	Pumping stopped frequently for short periods of time
76	-	11:12	11:17	-	5	Pumping stopped frequently for short periods of time
77	-	11:15	11:24	-	9	Pumping stopped frequently for short periods of time
78	-	11:22	11:30	-	8	Pumping stopped frequently for short periods of time
79	-	11:26	11:32	-	6	Pumping stopped frequently for short periods of time
80	-	11:30	11:39	-	9	Pumping stopped frequently for short periods of time

Table D.9 – Individual Burlap Placement Times for LC-HPC Bridge Decks

Location	Time					Notes
	Place Concrete in Forms	Strike Off	Place Burlap First Layer	Place Burlap Second Layer	Time to Burlap (min.)	
81	-	11:32	11:44	-	12	Pumping stopped frequently for short periods of time
82	-	11:40	11:49	-	9	Pumping stopped frequently for short periods of time
83	-	11:50	11:58	-	8	-
84	-	11:55	12:02	-	7	Some large voids on surface after finishing
85	-	12:00	12:04	-	4	Some large voids on surface after finishing
86	-	12:08	12:22	-	14	Some large voids on surface after finishing
87	-	12:20	12:27	-	7	End of placement
LC-HPC-7 (43-033) Qualification Slab, Cast on 6/8/2006						
0	-	6:27	6:46	-	19	Strike-off at 5:59; Pan finish at 6:27
End	-	7:03	7:08	-	5	-
LC-HPC-7 (43-033) Deck, Cast on 6/24/2006						
0	-	-	-	-	26	2^{nd} layer at 13 min. after 1^{st} layer
0.5 L	-	-	-	-	16	2^{nd} layer at 11 min. after 1^{st} layer
0.5 L + 30 ft	-	-	-	-	11	2^{nd} layer at 7 min. after 1^{st} layer
Last 10 ft.	-	-	-	-	90	-
LC-HPC-8 (54-053) Qualification Slab, Cast on 9/26/2007						
3 ft	8:30	9:10	9:22	-	12	Sprayed water on the dry burlap
7	8:48	9:16	9:32	-	16	Fogging – can see water on the deck.
15	-	9:23	-	-	-	Burlap is dry when placed.

Table D.9 – Individual Burlap Placement Times for LC-HPC Bridge Decks

Location	Time					Notes
	Place Concrete in Forms	Strike Off	Place Burlap First Layer	Place Burlap Second Layer	Time to Burlap (min.)	
20	-	9:33	9:40	-	7	Old burlap.
LC-HPC-8 (54-053) Deck, Cast on 10/3/2007						
NW wingwall	7:38	-	-	-	-	Placement began at 7:38
SW wingwall	7:52	-	-	-	-	-
1 (3 ft.)	8:01	8:28	8:38	-	10	Stared from west side
2 (10 ft)	8:19	8:31	8:47	-	16	-
3 (20 ft)	8:28	8:41	8:52	-	11	-
4	8:38	8:52	9:06	-	14	Delay due to filling the 1st diaphragm
5	8:47	9:09	9:16	-	7	-
6	-	9:17	9:24	-	7	-
7	9:15	9:26	9:38	-	12	1st diaphragm
8	9:22	9:38	9:44	-	6	-
9	9:35	9:44	9:54	-	10	-
10	-	9:54	10:02	-	8	10:02-10:04 Delay due to pumping
11	9:50	10:06	10:14	-	8	-
12	-	10:13	10:21	-	8	-
13	-		10:43	-		Delay due to filing 2nd diaphragm
14	-	10:44	10:57	-	13	2 short pieces of burlap used at this location; previous locations used one piece
15	10:45	10:56	11:06	-	10	-
16	10:51	11:07	11:17	-	10	2nd diaphragm

Table D.9 – Individual Burlap Placement Times for LC-HPC Bridge Decks

Location	Time					Notes
	Place Concrete in Forms	Strike Off	Place Burlap First Layer	Place Burlap Second Layer	Time to Burlap (min.)	
17	11:00	11:16	11:27	-	11	Slow due to concrete
18	11:12	11:23	11:33	-	10	-
19	11:20	11:33	11:43	-	10	-
20	-	-	11:52	-	-	Old burlap was used from 185 ft to 195 ft. (some big holes)
21	11:38	11:53	12:04	-	11	11:50 changed pump
23	11:53	12:23	12:36	-	13	Delay due to filling the 3rd diaphragm
24	12:19	12:32	12:36	-	4	Old burlap used from 214 ft to 233 ft.
25	-	12:48	1:01	-	13	Delay due to concrete
26	-	1:02	1:13	-	11	3rd diaphragm
27	-	1:13	1:25	-	12	-
28	1:08	1:21	1:37	-	16	-
29	1:14	1:32	1:51	-	19	Filled east abutment and wingwalls
30	-	1:48	2:06	-	18	-
31	-	1:55	2:10	-	15	-
32	-	2:09	2:36	-	27	Backordered concrete. Fogging turned on from 2:15 to 2:30.
Last 3 ft.	-	2:32	2:44	-	12	-
LC-HPC-10 (54-060) Qualification Slab, Cast on 4/26/2007						
0 L	-	10:08	10:53	-	45	-
0.5 L	-	11:04	11:11	-	7	-
1.0 L	-	11:07	11:15	-	8	-

Table D.9 – Individual Burlap Placement Times for LC-HPC Bridge Decks

Location	Time					Notes
	Place Concrete in Forms	Strike Off	Place Burlap First Layer	Place Burlap Second Layer	Time to Burlap (min.)	
LC-HPC-10 (54-060) Deck, Cast on 5/17/2007						
Abutment	4:30	-	-	-	-	Started placing concrete at 4:30
SE wingwall	4:30	4:47	-	-	-	-
NE wingwall	4:30	4:52	5:23	-	31	-
Form 1	4:45	4:58	5:25	-	27	Distance between forms is approximately 9.6 ft.
3	5:12	5:35	5:53	-	18	-
4	5:20	5:55	6:15	-	20	-
6	5:46	6:05	6:23	-	18	-
7	5:53	6:16	6:32	-	16	-
9	6:09	6:40	6:55	-	15	-
10	6:30	6:57	7:05	-	8	Roller started moving faster
11	6:37	7:05	7:15	-	10	-
12	-	7:13	7:19	-	6	-
14	6:57	7:24	7:52	-	28	Delay due to concrete
15	-	7:55	8:10	-	15	-
17	7:50	8:07		-		Negative moment region
19	-	8:25	8:32	-	7	Change the pump location
20	-	9:10	9:20	-	10	-
22	-	9:20	9:26	-	6	-
24	-	9:30	9:46	-	16	Some burlap workers changed jobs to work on fogging.
26	-	10:00	10:17	-	17	-
30	-	10:29	10:39	-	10	-
End (last 20 ft)	-	11:30	12:11	-	41	10:55 to 11:20 Delay due to concrete.

Table D.9 – Individual Burlap Placement Times for LC-HPC Bridge Decks

Location	Time					Notes
	Place Concrete in Forms	Strike Off	Place Burlap First Layer	Place Burlap Second Layer	Time to Burlap (min.)	
LC-HPC-9 (54-057) Qualification Slab, Attempt 3 Cast on 4/1/2009						
-	10:55	-	-	-	-	Waiting for concrete testing after the conveyor and the 2nd concrete truck.
0	11:23	11:31	11:48	-	17	2 pans, no bullfloat. Finishing well. Burlap has dry spots.
0.25 L	-	11:44	-	-	12	Burlap has dry spots.
0.5 L	-	11:50	11:58	-	8	-
0.6 L	-	11:53	12:02	-	9	12:02 Rewet placed burlap by spraying
0.75 L	-	11:55	12:07	-	12	-
End	-	12:01	12:07	-	6	-
LC-HPC-9 (54-057) Deck, Cast on 4/15/2009						
1	10:05 a.m.	10:44	10:53	-	9	9:30 a.m. First truck arrived.
2	10:29	10:52	11:06	-	14	10:00 Concrete placed in deck.
3	10:36	11:13	11:18	-	5	-
4	10:43	11:25	11:30	-	5	-
5	11:00	11:40	11:46	-	6	-
6	11:09	11:49	11:55	-	6	-
7	11:16	11:58	12:04	-	6	11:16 Moving pump truck.
8	11:40	12:06	12:14	-	8	-
9	11:47	12:24	12:35	-	11	Delay due to switching pumps.
10	11:57	12:44	12:53	-	9	-
11	12:17	12:52	1:04	-	12	-
12	12:36	1:03	1:13	-	10	-
13	12:47	1:10	1:16	-	6	-

Table D.9 – Individual Burlap Placement Times for LC-HPC Bridge Decks

Location	Time					Notes
	Place Concrete in Forms	Strike Off	Place Burlap First Layer	Place Burlap Second Layer	Time to Burlap (min.)	
14	12:58	1:15	1:25	-	10	1:25 Placed dry burlap
15	1:05	1:23	1:29	-	6	Spraying burlap.
16	1:14	1:29	1:36	-	7	1:30 Soaker hoses placed
17	1:19	1:35	1:49	-	14	-
18	1:26	1:44	1:58	-	14	-
19	1:39	1:55	2:04	-	9	-
20	1:42	2:02	2:15	-	13	-
21	1:47	2:15	2:20	-	5	-
22	2:01	2:22	2:31	-	9	-
23	2:05	2:28	2:38	-	10	-
24	2:16	2:41	2:54	-	13	2:40 Move pump truck
25	2:25	2:57	3:01	-	4	-
26	2:31	3:04	3:14	-	10	-
27	2:37	3:12	3:25	-	13	-
28	3:02	3:26	3:42	-	16	-
29	3:12	3:43	3:46	-	3	-
30	3:17	3:45	3:51	-	6	-
31	3:26	3:52	3:59	-	7	-
32	3:39	3:57	4:10	-	13	-
33	3:45	4:02	4:20	-	18	-
34	3:50	4:17	4:25	-	8	-
35	3:56	4:20	4:33	-	13	-
36	4:14	4:33	4:43	-	10	-
37	4:24	4:40	4:50	-	10	4:50 Moved truck
38	4:31	4:45	4:59	-	14	-
39	4:38	4:54	5:05	-	11	-

Table D.9 – Individual Burlap Placement Times for LC-HPC Bridge Decks

Location	Time					Notes
	Place Concrete in Forms	Strike Off	Place Burlap First Layer	Place Burlap Second Layer	Time to Burlap (min.)	
40	4:44	5:03	5:15	-	12	-
41	4:55	5:14	5:25	-	11	-
42	5:01	5:20	5:30	-	10	5:25 Ran out of concrete
43	5:10	5:35	5:45	-	10	5:45 Covered concrete during delay waiting for concrete
End	5:57	6:07	6:19	-	12	5:50 Concrete arrived.
LC-HPC-11 (78-119) Qualification Slab, Cast on 5/25/2007						
3 ft	11:58	12:50	1:30	1:30	40	Finished the first 2 ft. manually
9	12:44	1:05	1:54	1:54	49	12:05-12:38 Delay due to concrete delivery
15	12:59	1:29	2:04	2:04	35	12:45-12:53 Delay due to concrete delivery
21	1:22	1:51	2:11	2:11	20	1:05-1:18 Delay due to concrete delivery
27	1:48	2:01	2:15	2:15	14	1:32-1:45 Delay concrete
33	1:54	-	-	-	-	Placed 2 layers of burlap together. Difficulties getting concrete out of the trucks. Space between work bridges too large. 6 people, 3 people/work bridge.
LC-HPC-11 (78-119) Deck, Cast on 6/9/2007						
West abutment	7:50 a.m.	8:11	8:26	-	15	5:55 a.m. First truck arrived.
Station 1	7:52	8:14	8:31	-	17	Distance between stations is approximately 7.5 ft. 15 ft between stations 1 and 3.

Table D.9 – Individual Burlap Placement Times for LC-HPC Bridge Decks

Location	Time					Notes
	Place Concrete in Forms	Strike Off	Place Burlap First Layer	Place Burlap Second Layer	Time to Burlap (min.)	
Station 1 Continued	-	-	-	-	-	Begin placing concrete with a conveyor belt.
3	-	8:32	8:51	-	19	7.5 ft. between stations 3 and 4. 8:34-8:48 Delay due to high concrete slump
4	8:22	8:48	9:07	-	19	Deliver wet burlap
5	8:33	9:00	9:17	-	17	Deliver wet burlap. 9:05 rewetting placed burlap because it was becoming dry.
6	8:50	9:09	9:21	-	12	Two additional workers to deliver burlap.
7	9:07	9:16	9:28	-	12	-
9	9:18	9:32	9:42	-	10	-
10	9:25	9:40	9:55	-	15	9:45-9:52 Change positions of conveyor belt
12	9:39	10:00	10:18	-	18	10:04-10:10 Began placing concrete in east abutment
13	9:56	10:17	10:21	-	4	-
14	10:12	10:47	11:00	-	13	10:28-10:41 Delay due to concrete
15	10:17	10:53	11:01	-	8	-
East abutment	-	10:55	11:10	-	15	-
LC-HPC-12 (56-057 Unit 2) Qualification Slab, Cast on 3/28/2008						
Beginning	-	9:42	9:52	-	10	-
3	-	9:47	9:52	-	5	-

Table D.9 – Individual Burlap Placement Times for LC-HPC Bridge Decks

Location	Time					Notes
	Place Concrete in Forms	Strike Off	Place Burlap First Layer	Place Burlap Second Layer	Time to Burlap (min.)	
4	-	9:49	-	-	-	Delay due to concrete.
5	-	9:50	-	-	-	Delay due to concrete.
Middle	-	11:10	11:18	-	8	-
6	-	11:46	11:49	-	3	-
7	-	11:47	11:51	-	4	-
8	-	12:04	12:08	-	4	-
9	-	12:06	12:11	-	5	-
10	-	12:12	12:15	-	3	-
LC-HPC-12 (56-057 Unit 2) Phase 1, Cast on 4/4/2008						
North end	9:32 a.m.	10:02	10:11	-	9	9:04 Began placing concrete in abutment.
1	-	10:04	10:11	-	7	-
2	-	10:08	10:19	-	11	-
3	-	10:17	10:24	-	7	-
4	-	10:29	10:35	-	6	-
5	-	10:40	10:49	-	9	-
6	-	10:50	10:58	-	8	-
7	-	11:01	11:06	-	5	-
8	-	11:10	11:18	-	8	-
9	-	11:20	11:27	-	7	-
12	-	11:42	11:49	-	7	-
13	-	11:59	12:05	-	6	-
18	-	12:38 p.m.	12:43	-	5	-
21	-	12:59	1:06	-	7	-
22	-	1:07	1:11	-	4	-
23	-	1:18	1:23	-	5	-

Table D.9 – Individual Burlap Placement Times for LC-HPC Bridge Decks

Location	Time					Notes
	Place Concrete in Forms	Strike Off	Place Burlap First Layer	Place Burlap Second Layer	Time to Burlap (min.)	
24	-	1:23	1:28	-	5	-
28	-	2:00	2:06	-	6	-
30	-	2:18	2:22	-	4	-
31	-	2:23	2:35	-	12	-
32	-	2:39	2:43	-	4	-
South end	-	2:44	2:56	-	12	-
LC-HPC-12 (56-057 Unit 2) Phase 2, Cast on 3/18/2009						
1	10:56 a.m.	11:42	11:58	-	16	10:52 Begin to place concrete in deck. 11:43 added pan drag.
2	11:05	11:59	12:09	-	10	11:33 Gang vibrators/screed begins between stations 1 and 2
3	11:30	12:10	12:22	-	12	-
4	12:03 p.m.	12:18	12:25	-	7	Burlap was dripping wet.
5	12:12	12:24	12:33	-	9	12:30 Started spraying the bridge with water.
6	12:16	12:38	12:44	-	6	12:40-1:08 Delay due to concrete
7	12:33	1:12	1:18	-	6	-
8	12:44	1:19	1:21	-	2	1:20-1:35 Delay due to concrete
9	1:10	1:38	1:42	-	4	-
10	1:15	1:48	1:54	-	6	-
11	1:37	1:54	1:59	-	5	-
12	1:47	2:01	2:19	-	18	2:01-2:08 Delay due to concrete
13	1:54	2:26	2:35	-	9	Delay due to concrete
14	2:15	2:39	2:45	-	6	-
15	2:33	2:47	2:49	-	2	-
16	2:38	2:53	2:57	-	4	-

Table D.9 – Individual Burlap Placement Times for LC-HPC Bridge Decks

Location	Time					Notes
	Place Concrete in Forms	Strike Off	Place Burlap First Layer	Place Burlap Second Layer	Time to Burlap (min.)	
17	2:44	2:59	3:03	-	4	-
18	2:49	3:04	3:16	-	12	Delay due to concrete
19	2:54	3:17	3:19	-	2	-
20	3:06	3:21	3:34	-	13	Delay due to concrete
21	3:19	3:37	3:41	-	4	-
22	3:26	3:43	4:07	-	24	Delay due to concrete. Small amount of water on the deck, was not worked in.
23	3:33	4:08	4:16	-	8	-
24	4:05	4:18	4:23	-	5	-
25	4:14	4:23	4:32	-	9	-
26	4:22	4:32	4:36	-	4	-
27	4:28	4:39	4:47	-	8	-
28	4:33	4:49	4:52	-	3	-
29	4:47	4:58	5:02	-	4	-
30	4:50	5:03	5:13	-	10	-
31	5:00	5:14	5:15	-	1	-
32	5:11	5:22	5:30	-	8	-
33	5:15	5:33	5:37	-	4	-
34	5:27	6:00	6:03	-	3	5:39-5:52 Delay due to concrete
35	5:38	6:04	6:07	-	3	-
36	5:58	6:12	6:17	-	5	-
37	6:02	6:23	6:26	-	3	-
38	6:11	6:29	6:31	-	2	-
39	6:20	6:57	7:01	-	4	-
40	6:27	7:02	7:06	-	4	Rail was left uncovered until 7:11

Table D.9 – Individual Burlap Placement Times for LC-HPC Bridge Decks

Location	Time					Notes
	Place Concrete in Forms	Strike Off	Place Burlap First Layer	Place Burlap Second Layer	Time to Burlap (min.)	
41	6:57	7:25	7:26	-	1	7:36 Removed work bridge
42	7:30	7:36	7:42	-	6	Abutment rail. 7:10-7:50 Delay due to last truck.
LC-HPC-13 (54-066) Qualification Slab, Cast on 4/16/2008						
2.5 ft	-	-	-	-	16	-
5	-	-	-	-	12	-
7.6	-	-	-	-	25	-
10.1	-	-	-	-	23	-
12.6	-	-	-	-	19	-
15.1	-	-	-	-	19	-
17.7	-	-	-	-	12	-
20.2	-	-	-	-	14	-
22.7	-	-	-	-	12	-
25.2	-	-	-	-	8	-
27.8	-	-	-	-	10	-
30.3	-	-	-	-	8	-
32.8	-	-	-	-	6	-
LC-HPC-13 (54-066) Deck, Cast on 4/29/2008						
1	-	-	-	-	13	-
2	-	-	-	-	13	-
3	-	-	-	-	13	-
4	-	-	-	-	16	-
5	-	-	-	-	17	-
6	-	-	-	-	13	-
7	-	-	-	-	14	-
8	-	-	-	-	14	-

Table D.9 – Individual Burlap Placement Times for LC-HPC Bridge Decks

Location	Time					Notes
	Place Concrete in Forms	Strike Off	Place Burlap First Layer	Place Burlap Second Layer	Time to Burlap (min.)	
9	-	-	-	-	17	-
10	-	-	-	-	8	-
11	-	-	-	-	-	-
12	-	-	-	-	-	-
13	-	-	-	-	14	-
14	-	-	-	-	9	-
15	-	-	-	-	19	-
16	-	-	-	-	8	-
17	-	-	-	-	8	-
18	-	-	-	-	9	-
19	-	-	-	-	7	-
20	-	-	-	-	10	-
21	-	-	-	-	3	-
22	-	-	-	-	9	-
23	-	-	-	-	6	-
24	-	-	-	-	2	-
25	-	-	-	-	3	-
26	-	-	-	-	20	-
27	-	-	-	-	11	-
28	-	-	-	-	5	-
29	-	-	-	-	24	-
30	-	-	-	-	7	-
31	-	-	-	-	18	-
32	-	-	-	-	14	-
33	-	-	-	-	16	-

Table D.9 – Individual Burlap Placement Times for LC-HPC Bridge Decks

Location	Time					Notes
	Place Concrete in Forms	Strike Off	Place Burlap First Layer	Place Burlap Second Layer	Time to Burlap (min.)	
LC-HPC-14 (46-363) Qualification Slab, Cast on 11/13/2007						
5	2:25	2:49	3:09	-	20	-
10	2:30	3:00	3:25	-	25	-
15	2:50	3:17	3:31	-	14	-
20	-	3:25	3:40	-	13	-
LC-HPC-14 (46-363) Deck Phase 1 Placement 1 – Attempt 2, Cast on 12/19/2007						
North abutment	9:12 a.m. – 10:00	-	-	-	-	Placed concrete out of truck directly into abutment.
0 ft	10:20	10:35	11:15	-	40	South abutment was already poured (11/19/2007)
6 ft	-	10:48	11:20	-	32	Using 3 pieces of burlap to cover the entire deck width. Placing double layers at the same time.
8	10:35	10:53	11:25	-	32	-
20	10:55	11:08	11:39	-	31	11:20-11:28 Moving the position of the conveyor belt.
32	11:08	-	-	-	-	-
44	11:34	11:39	12:07	-	28	-
56	11:45	11:57	12:28	-	31	12:15-12:21 Conveyor belt was blocked. Changed the method of placing burlap. Now placing a single layer, then another layer separately.
68	11:57	12:12	12:46	-	34	12:28-12:33 Delay due to moving the conveyor belt

Table D.9 – Individual Burlap Placement Times for LC-HPC Bridge Decks

Location	Time					Notes
	Place Concrete in Forms	Strike Off	Place Burlap First Layer	Place Burlap Second Layer	Time to Burlap (min.)	
80	-	12:43	1:06	-	23	-
92	12:47	1:00	1:22	-	22	-
104	-	1:12	1:32	-	20	-
116	-	1:22	1:46	-	24	-
128	-	1:38	2:04	-	26	1:36-1:45 Delay due to waiting for concrete
140	-	1:57	2:23	-	26	-
152	-	2:13	2:36	-	23	-
164	-	2:30	2:52	-	22	-
176	-	2:51	3:24	-	33	3:05-3:15 Delay due to waiting for concrete
188	-	3:18	3:45	-	27	-
200 (end)	-	3:40	4:08	-	28	-
LC-HPC-14 (46-363) Deck Phase 2 Placement 2, Cast on 5/2/2008						
Roadway						
1 (3 ft)	10:00 a.m.	10:42	11:07	-	25	-
	10:30	10:46	11:10	-	24	-
2	10:35	10:50	11:12	-	22	-
	10:45	10:54	11:19	-	25	-
3	10:48	11:03	11:21	-	18	-
	10:53	11:13	11:25	-	20	Spraying water in SW direction at 11:24 (location 3.5)
4	11:00	11:18	11:31	-	13	-
	-	11:22	11:37	-	15	-
5	-	11:29	11:42	-	13	-
	-	11:35	11:53	-	18	-

Table D.9 – Individual Burlap Placement Times for LC-HPC Bridge Decks

Location	Time					Notes
	Place Concrete in Forms	Strike Off	Place Burlap First Layer	Place Burlap Second Layer	Time to Burlap (min.)	
6	11:23	11:41	12:04	-	23	-
	11:31	11:48	12:08	-	20	-
7	11:39	12:00	12:15	-	15	-
	-	12:06	12:20	-	14	-
8	11:49	12:13	12:32	-	19	-
	-	12:20	12:36	-	16	-
9	12:08	12:28	12:44	-	16	-
	12:15	12:34	12:48	-	14	-
10	12:21	12:40	12:52	-	12	-
	-	12:45	1:02	-	17	-
11	12:37	12:51	1:06	-	15	-
	12:45	12:59	1:19	-	20	-
12	-	1:05	1:25	-	20	-
	12:50	1:13	1:31	-	18	-
13	1:01	1:21	1:40	-	19	-
	-	1:31	1:49	-	18	-
14	1:14	1:39	1:54	-	15	-
	1:21	1:45	2:08	-	23	-
15	1:26	1:51	2:13	-	22	-
	1:32	2:00	2:42	-	42	Huge delays while waiting for concrete and vibrating/screeding.
16	1:42	2:10	3:24	-	74	-
	1:56	3:10	3:50	-	40	-
17	2:30	3:30	4:01	-	31	-

Table D.9 – Individual Burlap Placement Times for LC-HPC Bridge Decks

Location	Time					Notes
	Place Concrete in Forms	Strike Off	Place Burlap First Layer	Place Burlap Second Layer	Time to Burlap (min.)	
17 Continued	3:05	3:50	4:04	-	14	Finishing and bullfloated into surface (last 5 ft). Abutment at 1:30. One #7 cylinder knowcked over at 4:00.
Sidewalk						
1	-	10:17	11:16	-	59	-
	-	10:38	11:16	-	38	-
2	-	10:45	11:16	-	31	-
	-	10:50	11:34	-	44	-
3	-	10:55	11:34	-	39	-
	-	11:05	11:34	-	29	-
4	-	11:11	11:34	-	23	-
	-	11:15	12:00	-	42	-
5	-	11:22	12:00	-	38	-
	-	11:30	12:00	-	30	-
6	-	11:35	12:00	-	25	-
	-	11:41	12:29	-	48	-
7	-	11:48	12:29	-	41	-
	-	12:00	12:29	-	29	-
8	-	12:06	12:54	-	48	-
	-	12:13	12:54	-	41	-
9	-	12:20	12:54	-	34	-
	-	12:28	12.54	-	26	-
10	-	12:34	1:14	-	40	-
	-	12:40	1:14	-	34	-
11	-	12:45	1:14	-	29	-

Table D.9 – Individual Burlap Placement Times for LC-HPC Bridge Decks

Location	Time					Notes
	Place Concrete in Forms	Strike Off	Place Burlap First Layer	Place Burlap Second Layer	Time to Burlap (min.)	
11 Continued	-	12:51	1:46	-	23	-
12	-	12:59	1:46	-	47	-
	-	1:05	1:46	-	41	-
13	-	1:13	1:46	-	33	-
	-	1:21	2:17	-	56	-
14	-	1:31	2:17	-	46	-
	-	1:39	2:17	-	38	-
15	-	1:45	2:17	-	32	-
	-	1:51	4:10	-	139	-
16	-	-	4:10	-	-	-
	-	-	4:10	-	-	-
17	-	-	4:10	-	-	-
LC-HPC-14 (46-363) Deck Phase 2 – Placement 3, Cast on 5/21/2008						
0	7:14 p.m.	7:32	7:51	-	19	6:38 p.m. Concrete arrived.
1	7:27	7:37	7:58	-	21	-
2	7:41	8:54	8:08	-	14	-
3	8:00	8:09	8:23	-	14	-
4	8:17	8:25	8:41	-	16	8:27-8:32 Delay in placement.
5	8:35	8:43	8:57	-	14	-
6	8:47	9:03	9:14	-	11	8:47 Delay in placement.
7	9:06	9:21	9:30	-	9	8:58 Conveyor stuck.
8	9:27	9:35	9:46	-	11	9:14-9:17 Delay in placement.
9	9:44	9:52	10:13	-	21	9:41-9:44 Delay in placement. Finishing at the end was not great.

Table D.9 – Individual Burlap Placement Times for LC-HPC Bridge Decks

Location	Time					Notes
	Place Concrete in Forms	Strike Off	Place Burlap First Layer	Place Burlap Second Layer	Time to Burlap (min.)	
Last 4 m	-	-	-	-	-	Last 4 m was hand finished.

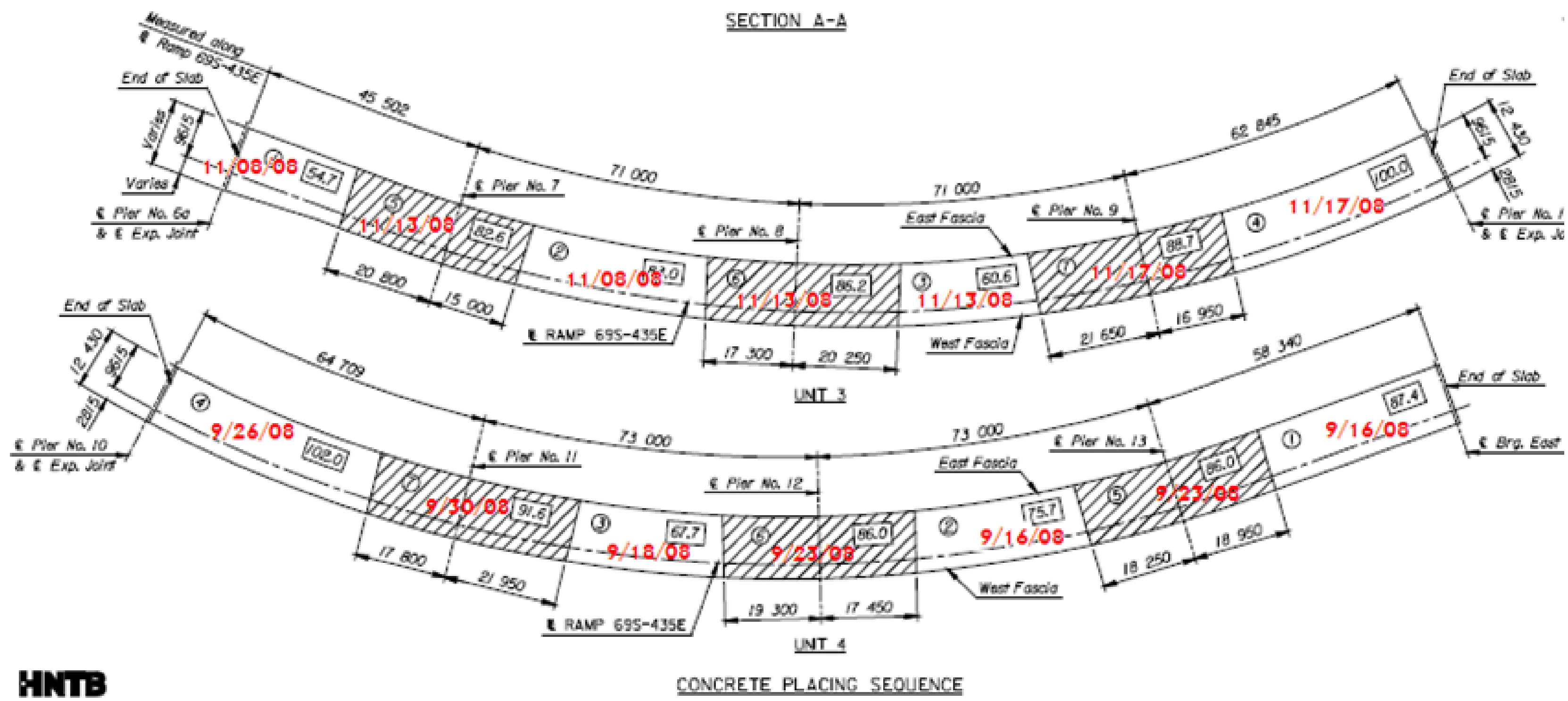


Fig. D.1 Casting sequence for Control 5 (Unit 3) and Control 6 (Unit 4).

APPENDIX E

CRACK DENSITY DATA

E.1 GENERAL

Appendix E contains preliminary crack density data for seven LC-HPC and seven Control bridge decks, including the date of the crack survey, age of the bridge deck, the crack density, the age-corrected crack density, and the mean age-corrected crack density for all surveys.

Table E.1 – Crack Densities for Individual Bridge Placements

LC-HPC Number	County and Serial Number	Portion Placed	Date of Placement	Survey #1				Survey #2	
				Date of Survey	Age (months)	Crack Density (m/m^2)	Age-Corrected Crack Density (m/m^2)	Date of Survey	Age (months)
1	105-304	South	10/14/2005	4/13/2006	5.9	0.012	0.102	4/30/2007	18.5
		North	11/2/2005	4/13/2006	5.3	0.003	0.094	4/30/2007	17.9
		Entire Deck	-	4/13/2007	-	0.007	0.098	4/30/2007	-
2	105-310	Deck	9/13/2006	4/20/2007	7.2	0.013	0.102	6/18/2008	21.2
Control 1/2	105-311	SFO North	10/10/2005	4/13/2006	6.1	0.000	0.204	4/30/2007	18.6
		SFO South	10/28/2005	4/13/2006	5.5	0.000	0.206	4/30/2007	18.0
		Entire Deck	-	4/13/2006	-	0.000	0.206	4/30/2007	-
Control 11	56-155	SFO	3/28/2006	8/13/2007	16.5	0.351	0.526	6/30/2008	27.1
3	46-338	Deck	11/13/2007	5/29/2008	6.5	0.028	0.118	-	-
4	46-339	South	9/29/2007	7/15/2008	9.5	0.004	0.090	-	-
		North	10/2/2007	7/15/2008	9.4	0.017	0.103	-	-
5	46-340 Unit 1	Deck	11/14/2007	7/15/2008	8.0	0.059	0.147	-	-
6	46-340 Unit 2	Deck	11/3/2007	5/20/2008	6.5	0.063	0.153	-	-
Control 3	46-337	SFO	7/17/2007	5/29/2008	10.4	0.037	0.229	-	-
Control 4	46-347	SFO	11/16/2007	6/10/2008	6.8	0.050	0.252	-	-
Control 7	46-334	SFO East 2/3	3/29/2006	8/10/2007	16.4	0.293	0.468	6/30/2008	27.1
		SFO West 3/3	9/15/2006	8/10/2007	10.8	0.030	0.221	6/30/2008	21.5
7	43-033	Deck	6/24/2006	6/5/2007	11.4	0.003	0.087	7/1/2008	24.2
Control 8/10	54-059	Deck	4/16/2007	6/26/2008	14.4	0.177	-	-	-
Control Alt	56-049	Deck	6/2/2005	6/2/2006	12.0	0.077	0.160	7/27/2007	25.8

Table E.1 (continued) – Crack Densities for Individual Bridge Placements

LC-HPC Number	Survey #2		Survey #3				All Surveys
	Crack Density (m/m^2)	Age-Corrected Crack Density (m/m^2)	Date of Survey	Age (months)	Crack Density (m/m^2)	Age-Corrected Crack Density (m/m^2)	Mean Age-Corrected Crack Density (m/m^2)
1	0.047	0.122	6/17/2008	32.1	0.044	0.102	0.109
	0.006	0.081	6/17/2008	31.5	0.024	0.082	0.086
	0.027	0.102	6/17/2008	-	0.034	0.092	0.098
2	0.028	0.099	-	-	-	-	0.101
Control 1/2	0.151	0.320	6/17/2008	32.2	0.114	0.244	0.256
	0.044	0.214	6/17/2008	31.6	0.091	0.223	0.214
	0.089	0.259	6/17/2008	-	0.099	0.231	0.232
Control 11	0.665	0.810	-	-	-	-	0.668
3	-	-	-	-	-	-	0.118
4	-	-	-	-	-	-	0.090
	-	-	-	-	-	-	0.103
5	-	-	-	-	-	-	0.147
6	-	-	-	-	-	-	0.153
Control 3	-	-	-	-	-	-	0.229
Control 4	-	-	-	-	-	-	0.252
Control 7	0.476	0.621	-	-	-	-	0.544
	0.069	0.229	-	-	-	-	0.225
7	0.019	0.086	-	-	-	-	-
Control 8/10	-	-	-	-	-	-	0.257
Control Alt	0.230	0.295	6/26/2008	36.8	0.219	0.271	0.242